Los agujeros negros no son tan negros: Breve Historia de la Ciencia de Stephen Hawking

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Factoría Joven
Badajoz, 17 de Abril de 2018

INSTITUTO DE LA JUVENTUD DE EXTREMADURA

Facultad de Ciencias

Servicio de Difusión de la Cultura Científica de la UEx

- *The most incomprehensible thing about the world is that it is comprehensible.*

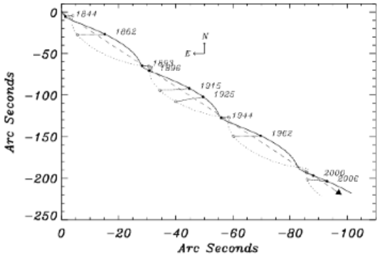
  (Albert Einstein)
- *It seems that there is a Chronology Protection Agency which prevents the appearance of closed timelike curves and so makes the universe safe for historians.*

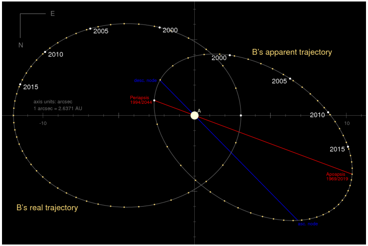
  (Stephen Hawking)

Stephen W. Hawking (1942-2018)

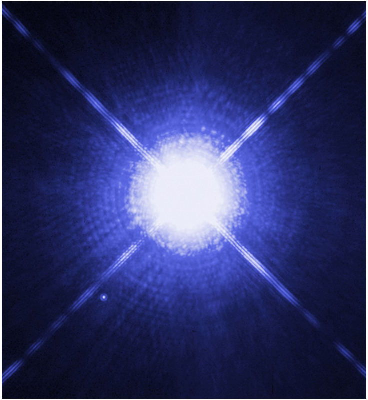
Sirio

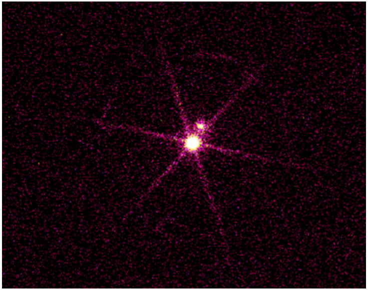
Sirio: Movimiento Propio





Sirio A y B





Estabilidad de las Estrellas

- Una esfera de polvo del tamaño y masa de la Tierra colapsará debido a la gravedad en unos 15 min.
- El primer freno del colapso graviatorio es la temperatura:

$$N k_B T \sim \frac{G M^2}{R_E}$$

$R = N_A k_B$. Recordatorio $p = nRT/V$. $T \sim 10^{10}$ K.

- Esta temperatura tan alta se mantiene mediante reacciones termonucleares.
- Cuando se llega al Fe, se bloquean las reacciones termonucleares y la estrella se empieza a enfriar y comienza su colapso gravitacional.
- El segundo freno es la presión de "degeneración cuántica" de los electrones.
- Si $M < M_{\mathrm{Ch}} \simeq 1.4 M_\odot$, los electrones frenan el colapso y el resultado final es una enana blanca.

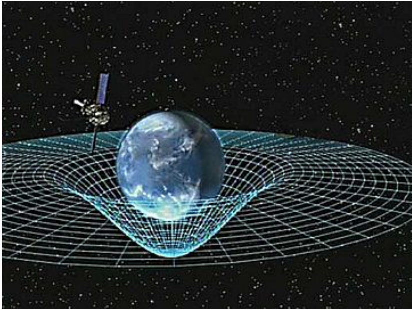
S. Chandrasekhar

Ecuaciones de Einstein (1915)

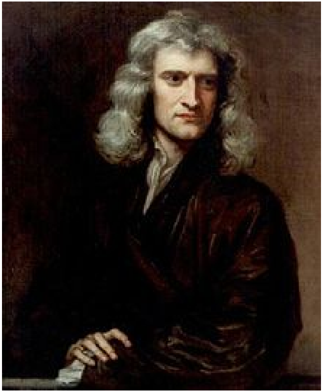
$$ds^2 = -c^2 d\tau^2 = g_{\alpha\beta} dx^\alpha dx^\beta$$

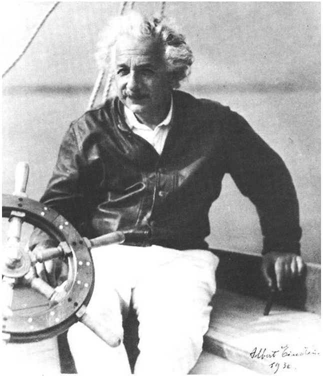
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\rho\gamma} \frac{dx^\rho}{d\tau} \frac{dx^\gamma}{d\tau} = 0$$



Newton/Einstein





$M > M_{\text{Ch}}$

- Si $M > M_{\text{Ch}}$ la estrella comienza a colapsar.
- Explosión Supernova.
- Decaimiento β usual:

$$n \to p + e^- + \overline{\nu}_e$$

- Decaimiento β inverso:

$$p + e^- \to n + \nu_e$$

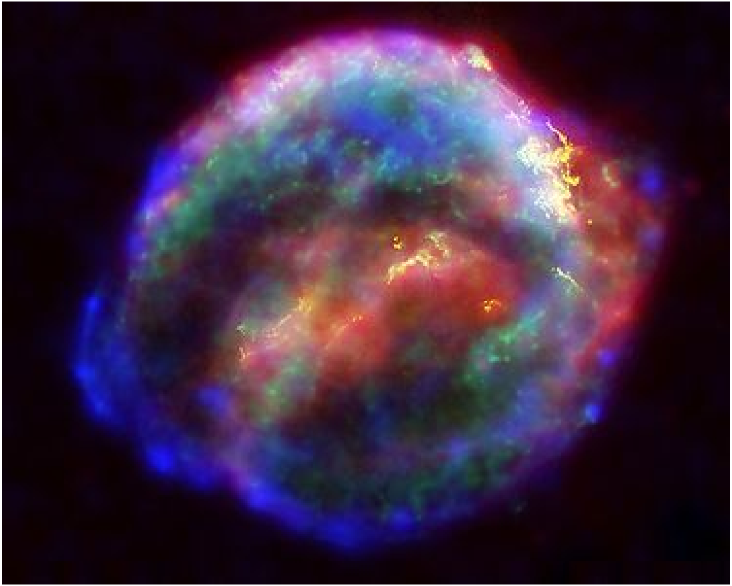
- Todos los protones y electrones se convierten en neutrones.
- El nucleo de la estrella se estabiliza mediante la “presión” de degeneración cuántica” de los neutrones si:

$$M < M_{\text{OV}} = 2.2 M_\odot$$

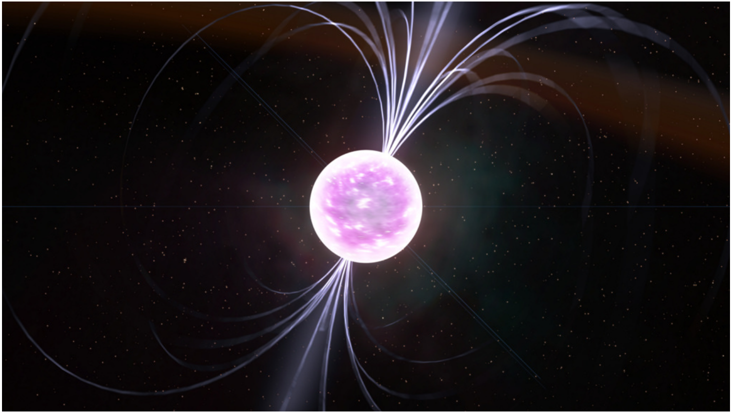
- Si $M > M_{\text{OV}}$ se producirá un Agujero Negro.

Oppenheimer/Landau

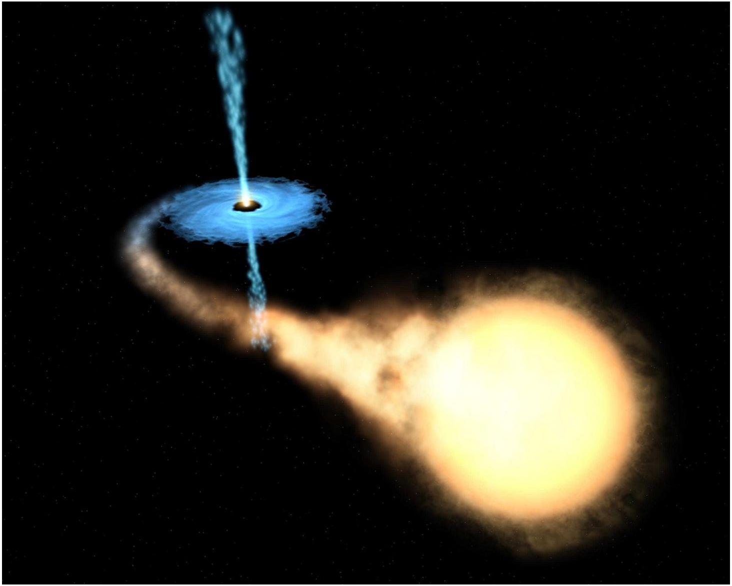
Supernova



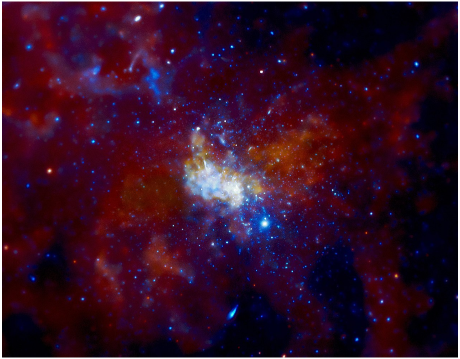
Estrella de neutrones

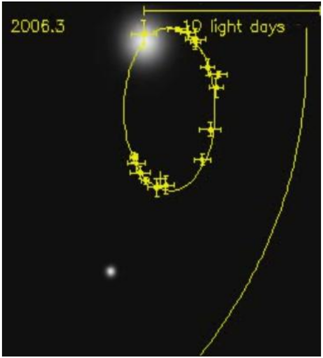


Agujero Negro: Binarias de rayos-X

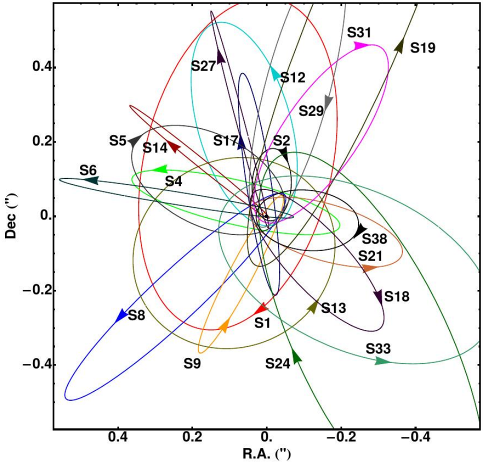


Agujero Negro Supermasivo: Sagitario A*



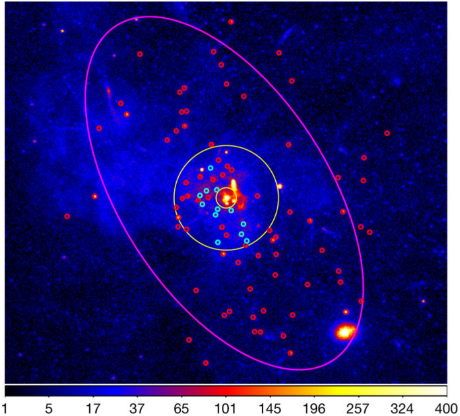


Agujero Negro Supermasivo: Sagitario A*



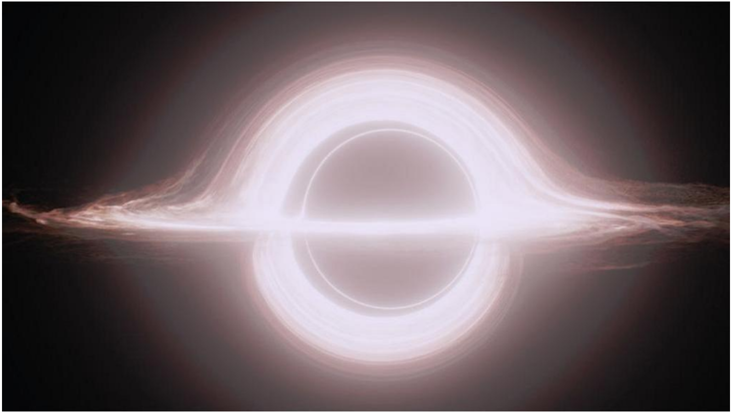
$$M \simeq 4 \times 10^6 M_\odot$$

Agujero Negro: Binarias de rayos-X

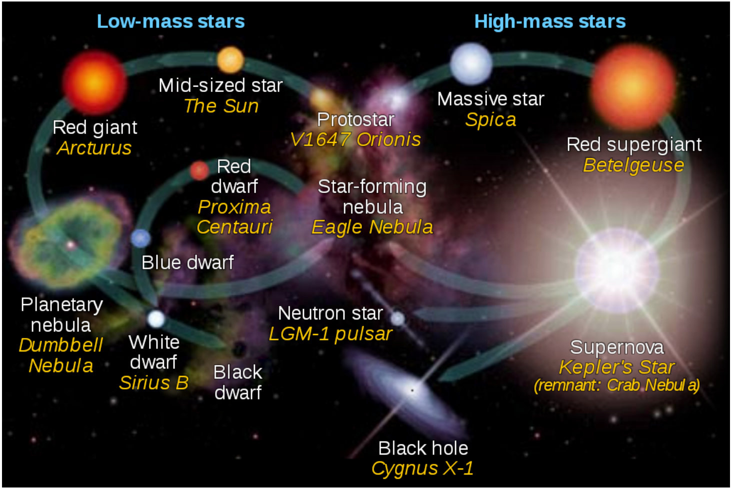


A density cusp of quiescent X-ray binaries in the central parsec of the Galaxy. *Nature* 556, 70–73 (5/Abril/2018).

Agujero Negro tipo Kerr (Gargantua)

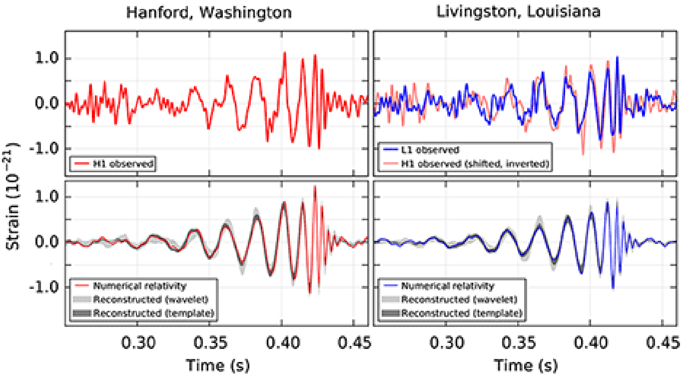


Etapas de la evolución Estelar (Resumen)



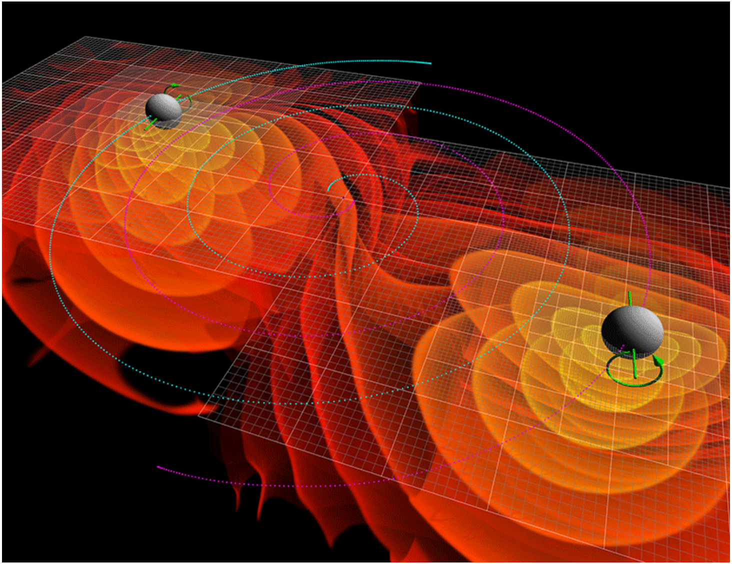
La señal

- Señal recibida el día 14/9/2015 a las 9:50:45 UTC en los observatorios de Livingston y Hanford (USA):

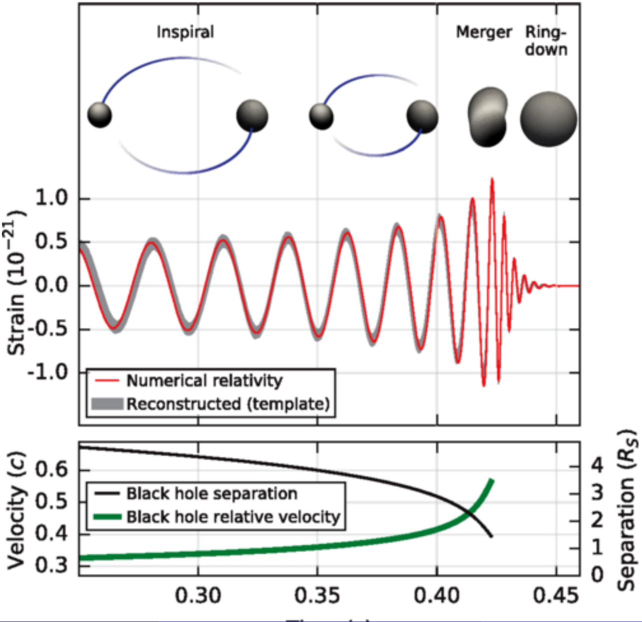


Laser Interferometer Gravitational-Wave Observatory (LIGO)

Ondas Gravitatorias



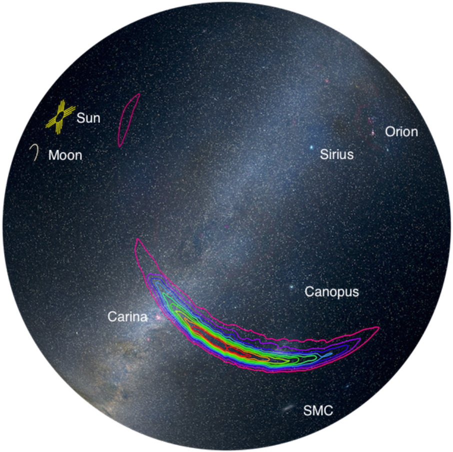
Señal de la Coalescencia de dos Agujeros Negros



Características de los dos Agujeros Negros

- Primario: $36 \pm 5\ M_\odot$
- Secundario: $29 \pm 4\ M_\odot$
- Masa Final: $62 \pm 4\ M_\odot$
- Momento angular final: 0.67 ± 0.07
- Distancia Luminosidad: 410 ± 180 Mpc
- Redshift (Cosmológico): 0.09 ± 0.04
- Energía total radiada: $3 \pm 0.5 M_\odot c^2$

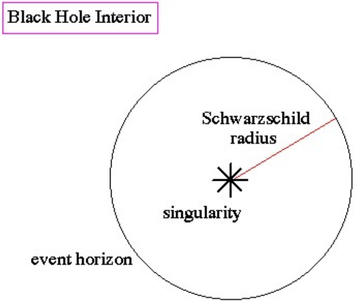
¿Dónde?

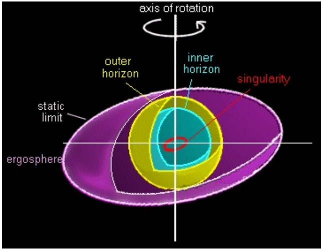


Clasificación de los Agujeros Negros

- Los agujeros negros no tienen pelo ("No hair theorem").
  - Schwarzschild ($M \neq 0$).
  - Kerr ($M \neq 0$, $J \neq 0$).
  - Reissner-Nordstrøm ($M \neq 0$, $Q \neq 0$).
  - Kerr-Newman ($M \neq 0$, $Q \neq 0$, $J \neq 0$).
- Principio de Censura Cósmica:
  No existen las singularidades desnudas.

Agujero Negros: Ejemplos





Velocidad de escape (Mitchell):

$$\frac{1}{2}mv^2 = \frac{GmM}{R}$$

$v = c \to R = R_s$:

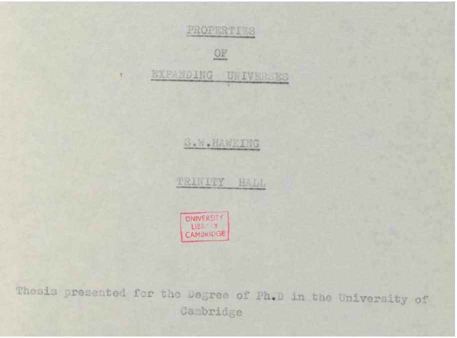
$$R_s = \frac{2GM}{c^2}$$

S. Hawking (infancia)

S. Hawking

S. Hawking (Oxford)

PhD Thesis, Cambridge



PROPERTIES

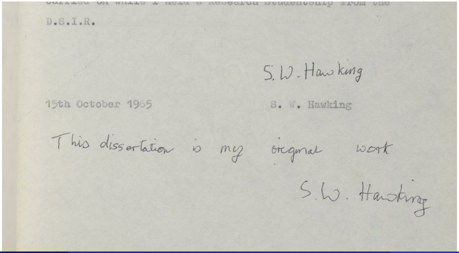
OF

EXPANDING UNIVERSES

S.W.HAWKING

TRINITY HALL

Thesis presented for the Degree of Ph.D in the University of Cambridge



carried on while I held a Research Studentship from the D.S.I.R.

S.W. Hawking

15th October 1965 S. W. Hawking

This dissertation is my original work

S.W. Hawking

PhD Thesis, Cambridge

generating Q^3 must have at least one singular point which means that they must be bounded in at least one direction. A simple example of s.C.s with a Cauchy horizon is a space-like surface of constant negative curvature completely within the null cone of the point in Minkowski space. The null cone forms the Cauchy horizon.

If conditions (c) and (g) hold, then a model with a compact s.C.s, H^3 must have the topology: $H^3 \times E^1$.

PROOF

Suppose there were a region V^4 through which there were no flow lines intersecting H^3, then V^3 the boundary of V^4 must be a time-like surface generated by flow-lines which do intersect H^3. Proceeding along these flow-lines in the direction of their intersection with H^3, we must reach an end-point of the generator since V^3 does not intersect H^3.

S. Hawking (familia)

Teoremas de Singularidad

Proc. Roy. Soc. Lond. A. **314**, 529–548 (1970)
Printed in Great Britain

The singularities of gravitational collapse and cosmology

By S. W. Hawking
Institute of Theoretical Astronomy, University of Cambridge

and R. Penrose
Department of Mathematics, Birkbeck College, London

(*Communicated by H. Bondi, F.R.S.—Received* 30 *April* 1969)

A new theorem on space-time singularities is presented which largely incorporates and generalizes the previously known results. The theorem implies that space-time singularities are to be expected if *either* the universe is spatially closed *or* there is an 'object' undergoing relativistic gravitational collapse (existence of a trapped surface) *or* there is a point p whose past null cone encounters sufficient matter that the divergence of the null rays through p changes sign somewhere to the past of p (i.e. there is a minimum apparent solid angle, as viewed from p for small objects of given size). The theorem applies if the following four physical assumptions are made: (i) Einstein's equations hold (with zero or negative cosmological constant), (ii) the energy density is nowhere less than minus each principal pressure nor less than minus the sum of the three principal pressures (the 'energy condition'), (iii) there are no closed timelike curves, (iv) every timelike or null geodesic enters a region where the curvature is not specially alined with the geodesic. (This last condition would hold in any sufficiently general physically realistic model.) In common with earlier results, timelike or null geodesic incompleteness is used here as the indication of the presence of space-time singularities. No assumption concerning existence of a global Cauchy hypersurface is required for the present theorem.

Commun. math. Phys. 31, 161–170 (1973)

The Four Laws of Black Hole Mechanics

J. M. Bardeen*

Department of Physics, Yale University, New Haven, Connecticut, USA

B. Carter and S. W. Hawking

Institute of Astronomy, University of Cambridge, England

Received January 24, 1973

Abstract. Expressions are derived for the mass of a stationary axisymmetric solution of the Einstein equations containing a black hole surrounded by matter and for the difference in mass between two neighboring such solutions. Two of the quantities which appear in these expressions, namely the area A of the event horizon and the "surface gravity" κ of the black hole, have a close analogy with entropy and temperature respectively. This analogy suggests the formulation of four laws of black hole mechanics which correspond to and in some ways transcend the four laws of thermodynamics.

Hawking en gravedad cero

Evaporación de los Agujeros Negros: Radiación de Hawking

Commun. math. Phys. 43, 199—220 (1975)

Particle Creation by Black Holes

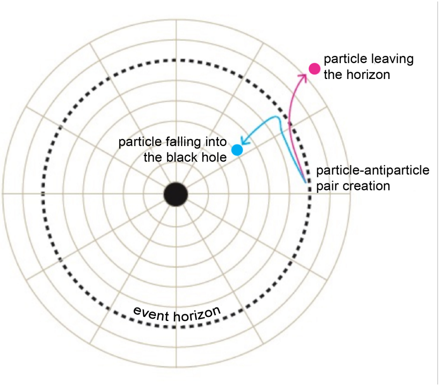
S. W. Hawking

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Received April 12, 1975

Abstract. In the classical theory black holes can only absorb and not emit particles. However it is shown that quantum mechanical effects cause black holes to create and emit particles as if they were hot bodies with temperature $\frac{\hbar\kappa}{2\pi k} \approx 10^{-6}\left(\frac{M_\odot}{M}\right)$ °K where κ is the surface gravity of the black hole. This thermal emission leads to a slow decrease in the mass of the black hole and to its eventual disappearance: any primordial black hole of mass less than about 10^{15} g would have evaporated by now. Although these quantum effects violate the classical law that the area of the event horizon of a black hole cannot decrease, there remains a Generalized Second Law: $S+\frac{1}{4}A$ never decreases where S is the entropy of matter outside black holes and A is the sum of the surface areas of the event horizons. This shows that gravitational collapse converts the baryons and leptons in the collapsing body into entropy. It is tempting to speculate that this might be the reason why the Universe contains so much entropy per baryon.

Radiación de Hawking



Principio de incertidumbre: $\Delta E \Delta t \sim h$.
Temperatura (cuerpo negro):

$$T = \frac{\hbar c^3}{G k_B} \frac{1}{8\pi M}$$

Evaporación de los Agujeros Negros

- Emisión: Potencia/Superficie $= \sigma T^4$

$$-\frac{d(Mc^2)}{dt} = \frac{1}{15360\pi}\frac{\hbar c^6}{G^2}\frac{1}{M^2}$$

$$t_e = \left(\frac{M}{230000\ \mathrm{kg}}\right)^3\ \mathrm{s}$$

- Ejemplos
  1. AN $M = M_\odot$: $t_e = 2\times 10^{67}$ años.
  2. AN $M = m_p$: $t_e = 3\times 10^{-97}$ s.

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Chronology protection conjecture

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(Received 23 September 1991)

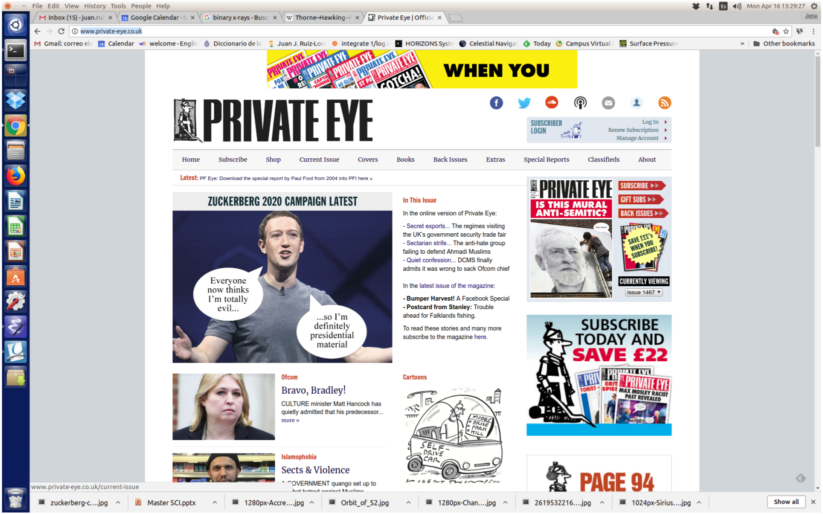
It has been suggested that an advanced civilization might have the technology to warp spacetime so that closed timelike curves would appear, allowing travel into the past. This paper examines this possibility in the case that the causality violations appear in a finite region of spacetime without curvature singularities. There will be a Cauchy horizon that is compactly generated and that in general contains one or more closed null geodesics which will be incomplete. One can define geometrical quantities that measure the Lorentz boost and area increase on going round these closed null geodesics. If the causality violation developed from a noncompact initial surface, the averaged weak energy condition must be violated on the Cauchy horizon. This shows that one cannot create closed timelike curves with finite lengths of cosmic string. Even if violations of the weak energy condition are allowed by quantum theory, the expectation value of the energy-momentum tensor would get very large if timelike curves become almost closed. It seems the back reaction would prevent closed timelike curves from appearing. These results strongly support the chronology protection conjecture: *The laws of physics do not allow the appearance of closed timelike curves.*

This was a form of insurance policy for me. I have done a lot of work on black holes, and it would all be wasted if it turned out that black holes do not exist. But in that case, I would have the consolation of winning my bet, which would win me four years of the magazine Private Eye. If black holes do exist, Kip will get one year of Penthouse. When we made the bet in 1975, we were 80% certain that Cygnus X-1 was a black hole. By now, I would say that we are about 95% certain, but the bet has yet to be settled.

Stephen Hawking, *A Brief History of Time (1988)*

In the updated and expanded edition of A Brief History of Time, Hawking states, "Although the situation with Cygnus X-1 has not changed much since we made the bet in 1975, there is now so much other observational evidence in favour of black holes that I have conceded the bet. I paid the specified penalty, which was a one year subscription to Penthouse, to the outrage of Kip's liberated wife."

Private Eye (16/4/2018)



The Euclidean path integral over all topologically trivial metrics can be done by time slicing and so is unitary when analytically continued to the Lorentzian. On the other hand, the path integral over all topologically non-trivial metrics is asymptotically independent of the initial state. Thus the total path integral is unitary and information is not lost in the formation and evaporation of black holes. The way the information gets out seems to be that a true event horizon never forms, just an apparent horizon.

Una copia de *Total Baseball, The Ultimate Baseball Encyclopedia.*

Stephen W. Hawking (1942-2018)