Evidences for Black Holes

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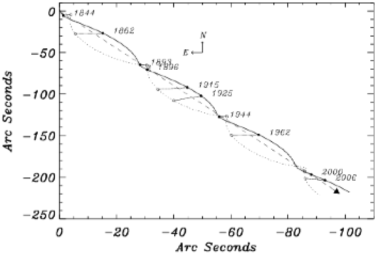
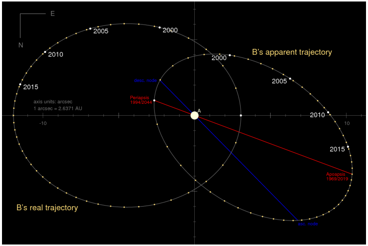
The most incomprehensible thing about the world is that it is comprehensible.

(Albert Einstein)

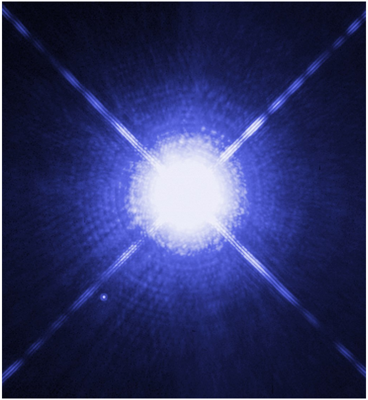
Sirius

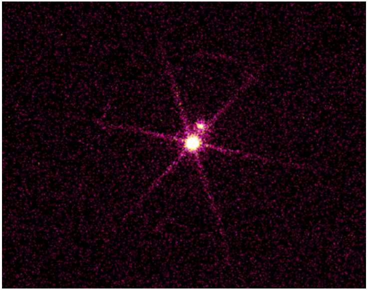
Sirius: Proper Motion





Sirius A and B





Stability of Starts

- A spherical star composed only by dust will collapse in about 15 min ($M = M_\odot$).
- The first mechanism to stop the collapse is the temperature:

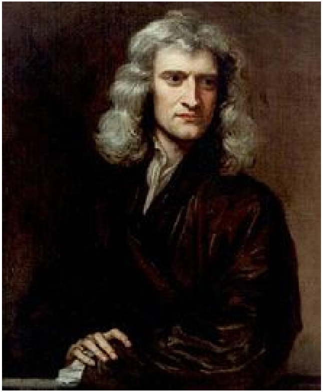
$$N k_B T \sim \frac{G M^2}{R}$$

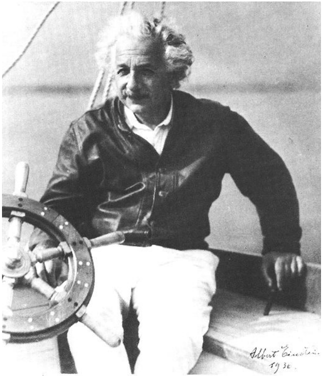
$R = N_A k_B$. Remember $p = nRT/V$. $T \sim 10^{10}$ K.

- The star is able to maintain this (high) temperature by means of thermo-nuclear reactions (fusion).
- Iron is the most stable nucleus, therefore, the thermo-nuclear reactions will stop in this chemical element, and the collapse will resume.
- The second mechanism to stop the collapse is the pressure produced by the quantum degeneracy of the electrons.
- If $M < M_{\rm Ch} \simeq 1.4 M_\odot$, the star will finish as a White dwarf.

S. Chandrasekhar

Newton/Einstein





$M > M_{\rm Ch}$

- If $M > M_{\rm Ch}$ the star will start to collapse.
- Supernovae explosion.
- Usual β decay:

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

- Inverse β decay:

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

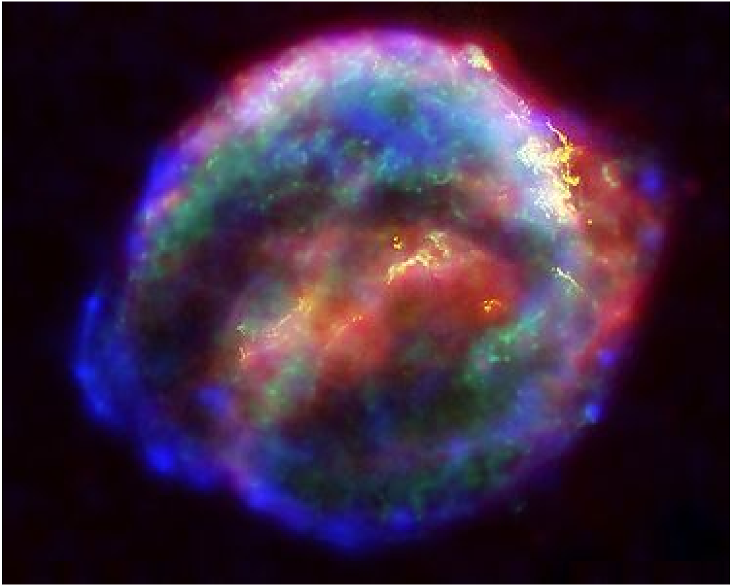
- Hence all the electrons and protons will turn into neutrons.
- The pressure generated by the quantum degeneracy of the neutrons will be able to stop the gravitational collapse if:

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

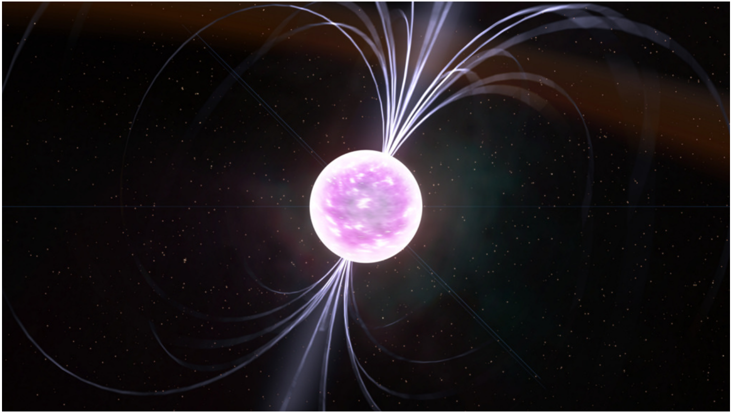
- Otherwise ($M > M_{\rm OV}$) the final state of this star will be a black hole .

Landau/Oppenheimer

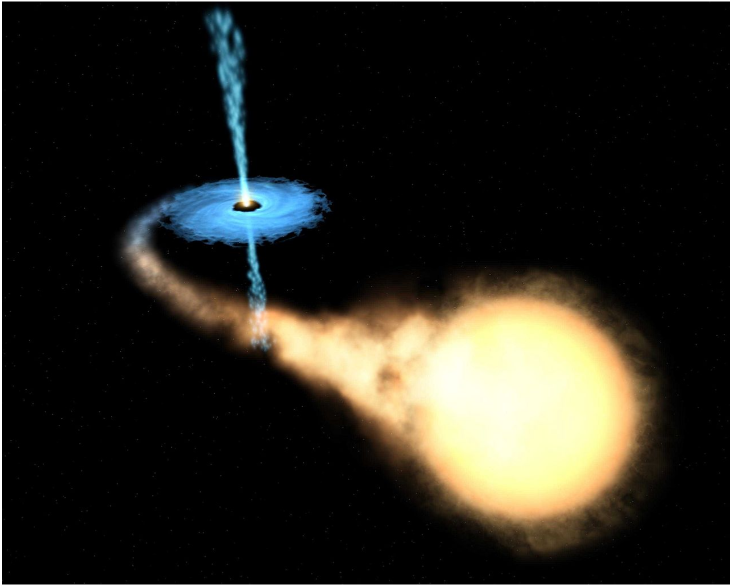
Supernovae



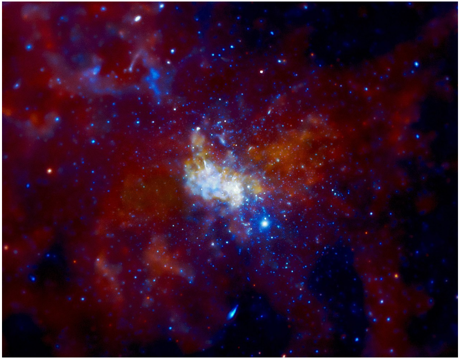
Neutron Star

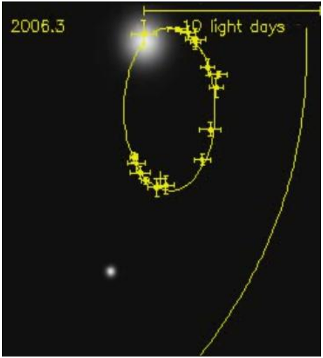


Black Hole: X-ray binaries

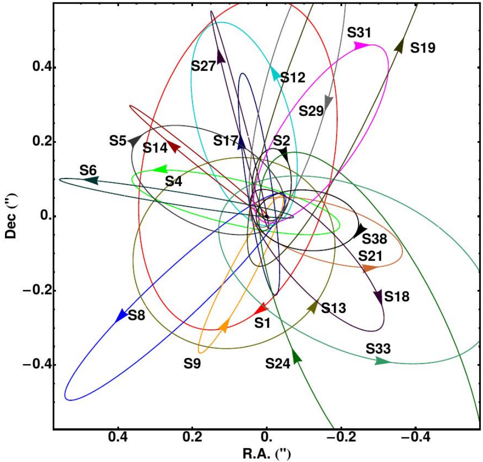


Supermassive Black Hole: Sagittarius A*



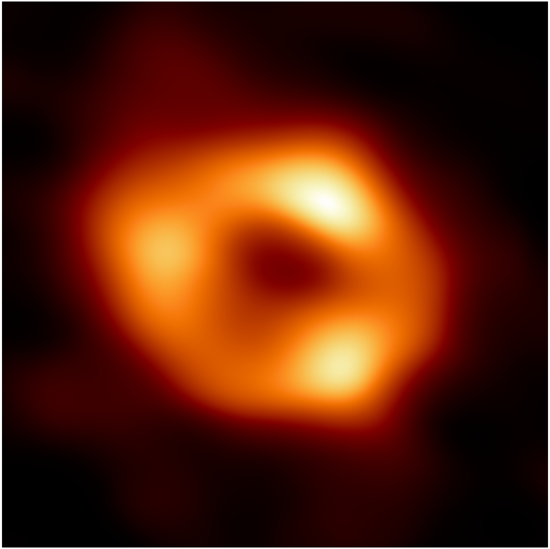


Supermassive Black Hole: Sagittarius A*

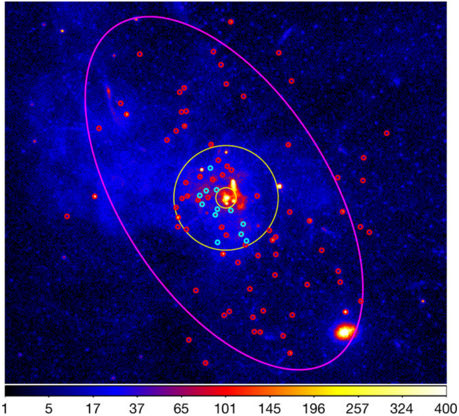


$$M \simeq 4 \times 10^6 M_\odot$$

Supermassive Black Hole: Sagittarius A*-EHT Telescope

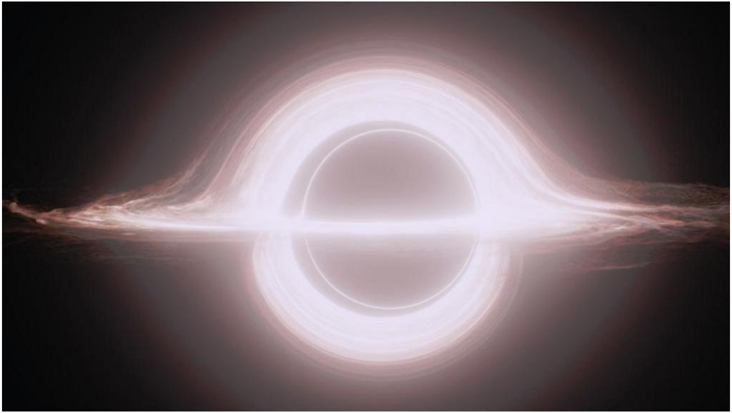


Black Hole: X-ray binaries

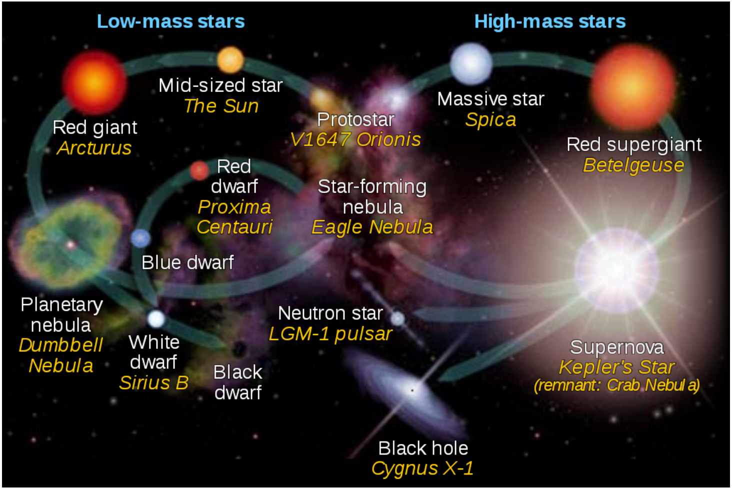


A density cusp of quiescent X-ray binaries in the central parsec of the Galaxy. *Nature* 556, 70–73 (5/Abril/2018).

Kerr's Black Hole (Gargantua)



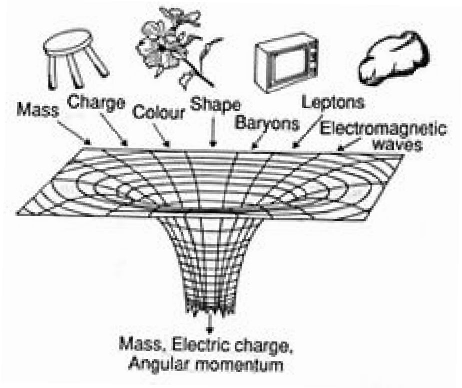
Steps of the stellar evolution (Summary)



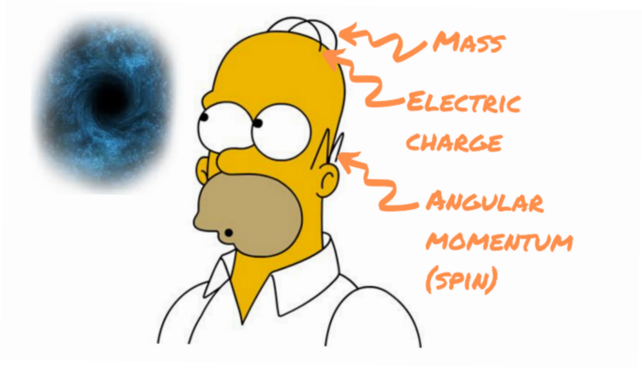
Black Hole's Classification

- "No hair theorem".
  - Schwarzschild ($M \neq 0$).
  - Kerr ($M \neq 0$, $J \neq 0$).
  - Reissner-Nordstrøm ($M \neq 0$, $Q \neq 0$).
  - Kerr-Newman ($M \neq 0$, $Q \neq 0$, $J \neq 0$).
- Cosmic Censorship Principle:
  There do not exist naked singularities.

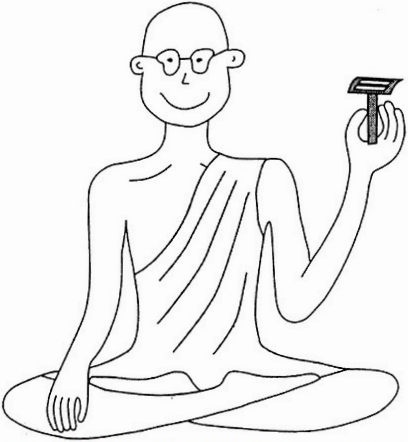
Stationary Black Holes Classification



Stationary Black Holes Classification



Stationary Black Holes Classification



According to the black hole **no-hair theorems**, an **electrically neutral rotating black hole** in General relativity is completely described by its **mass M** and **angular momentum S**

Singularity Theorems (Penrose, 1965)

VOLUME 14, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1965

GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

Roger Penrose
Department of Mathematics, Birkbeck College, London, England
(Received 18 December 1964)

The discovery of the quasistellar radio sources has stimulated renewed interest in the question of gravitational collapse. It has been suggested by some authors[1] that the enormous amounts of energy that these objects apparently emit may result from the collapse of a mass of the order of $(10^6\text{-}10^8)M_\odot$ to the neighborhood of its Schwarzschild radius, accompanied by a violent release of energy, possibly in the form of gravitational radiation. The detailed mathematics measured by local comoving observers, the body passes within its Schwarzschild radius $r=2m$. (The densities at which this happens need not be enormously high if the total mass is large enough.) To an outside observer the contraction to $r=2m$ appears to take an infinite time. Nevertheless, the existence of a singularity presents a serious problem for any complete discussion of the physics of the interior region.

Singularity Theorems (Hawking and Penrose, 1970

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.

Black Hole "Thermodynamics" (1973)

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.

Black Hole Thermodynamics (Bekenstein, 1973)

PHYSICAL REVIEW D VOLUME 7, NUMBER 8 15 APRIL 1973

Black Holes and Entropy*

Jacob D. Bekenstein†
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
and Center for Relativity Theory, The University of Texas at Austin, Austin, Texas 78712‡
(Received 2 November 1972)

There are a number of similarities between black-hole physics and thermodynamics. Most striking is the similarity in the behaviors of black-hole area and of entropy: Both quantities tend to increase irreversibly. In this paper we make this similarity the basis of a thermodynamic approach to black-hole physics. After a brief review of the elements of the theory of information, we discuss black-hole physics from the point of view of information theory. We show that it is natural to introduce the concept of black-hole entropy as the measure of information about a black-hole interior which is inaccessible to an exterior observer. Considerations of simplicity and consistency, and dimensional arguments indicate that the black-hole entropy is equal to the ratio of the black-hole area to the square of the Planck length times a dimensionless constant of order unity. A different approach making use of the specific properties of Kerr black holes and of concepts from information theory leads to the same conclusion, and suggests a definite value for the constant. The physical content of the concept of black-hole entropy derives from the following generalized version of the second law: When common entropy goes down a black hole, the common entropy in the black-hole exterior plus the black-hole entropy never decreases. The validity of this version of the second law is supported by an argument from information theory as well as by several examples.

Black Hole Evaporation: Hawking Radiation (1975)

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

Particle Creation by Black Holes

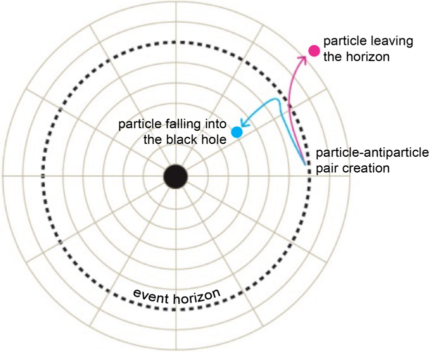
S. W. Hawking

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.

Hawking Radiation



Uncertainty Principle: $\Delta E \Delta t \sim h$.
Temperature (black body):

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

Black Hole Evaporation

- Emission: Power/Surface $= \sigma T^4$

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

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

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