Mysterious Black Holes

Pierre Vanhove

IPhT Saclay & Высшая школа экономики

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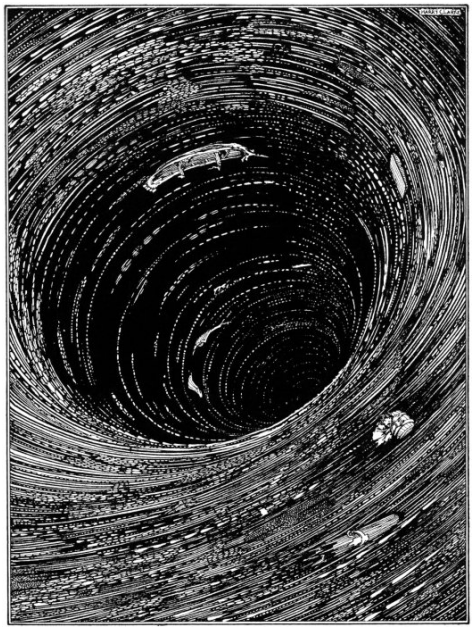
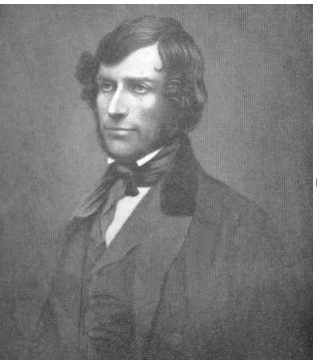


Les physiciens disent des trous noirs qu'à force de se concentrer dans le ciel nocturne, il leur arrive d'enrouler, dans la substance ténébreuse, l'espace qu'ils épanchent dans le temps.

Pascal Quignard (La barque silencieuse Chap XXV Extase et enstase)

Black star

In 1676 Ole Rømer proposed that speed of light is finite



In 1784 father John Michell proposed that from light cannot escape from a very massive object. His arguments are largely ignored

In 1796 Pierre-Simon de Laplace rediscover this idea

Classical gravitational radius

If light has a finite speed c then a very massive object can hold it

$$\frac{m_i c^2}{2} = \frac{G m_g M}{r} \Leftrightarrow r = \frac{2GM}{c^2} \frac{m_g}{m_i}$$

The equality between inertial m_i and gravitational m_g mass implies

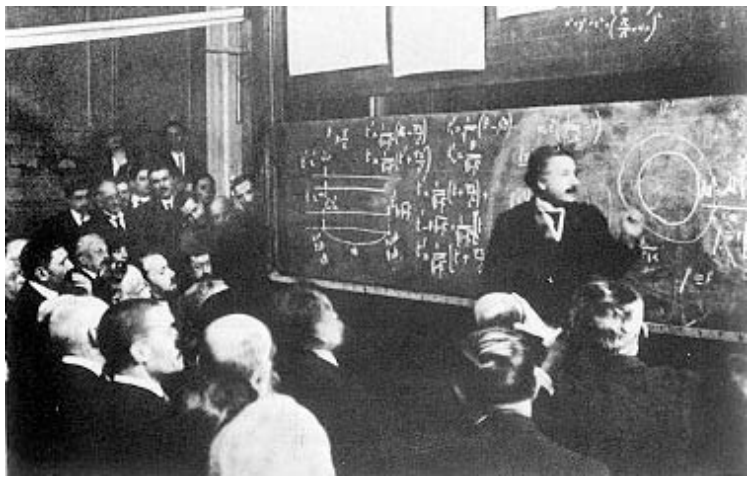
$$r_S = \frac{2GM}{c^2}$$

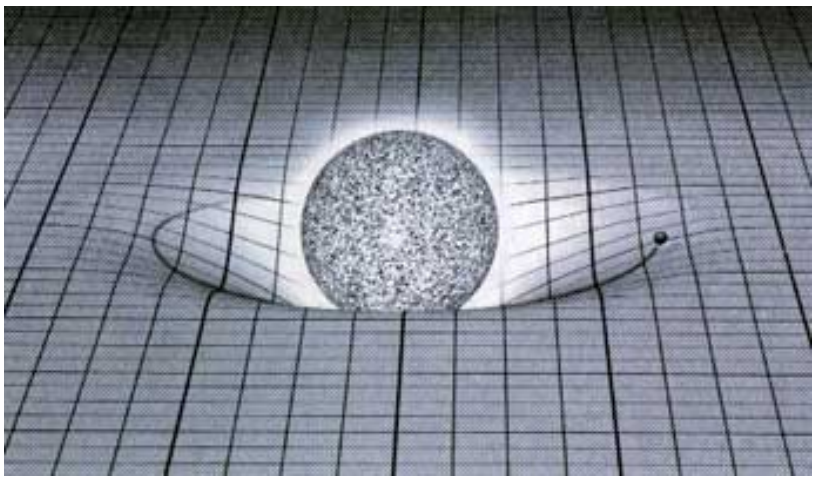
The result is correct but the reasoning is incorrect as any object with speed greater than the speed of light would escape!

The black star fall into obscurity till revived by Einstein theory of gravity

Gravity as spacetime bending

Novembre 25th 1915, Einstein presents his theory of gravity



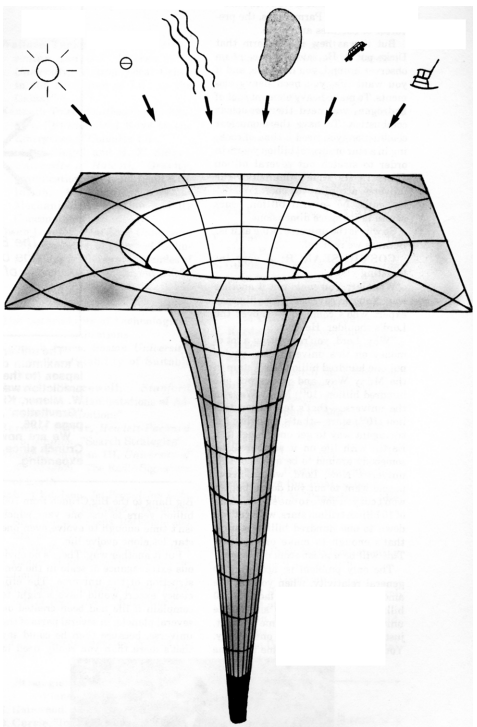


Space-time is bend by gravity

Body are not attracted but freely move along the geodesics of a curved space-time

The most perfect macroscopic objects

The most perfect macroscopic objects there are in the universe : the only elements in their construction are our concepts of space and time (S. Chandrasekhar)

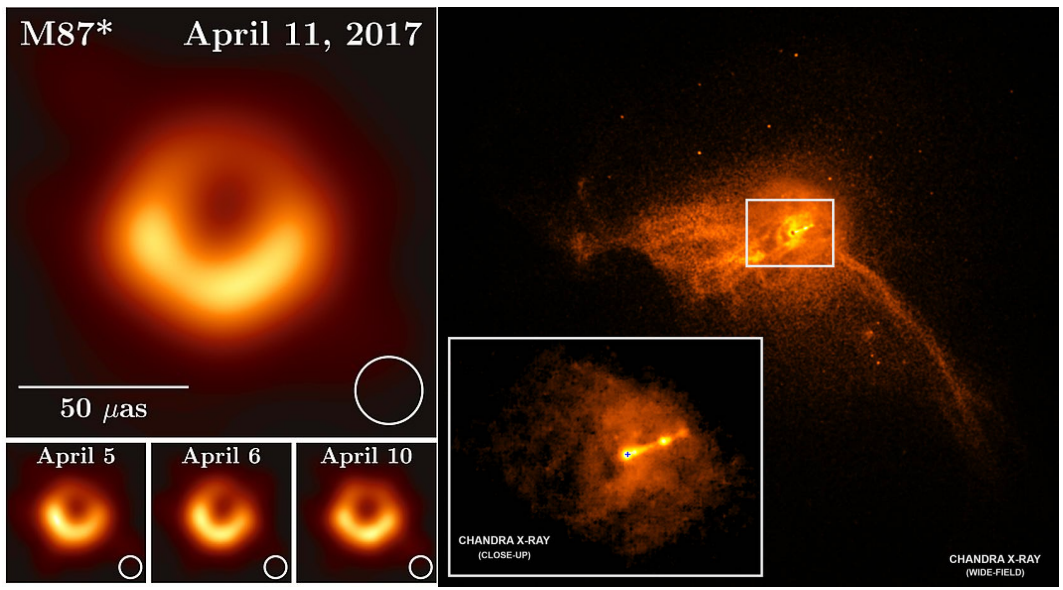


- Caractérisés par la géométrie extérieure
  - Mass $M_{\bullet}$
  - Angular momentum $\vec{J}$
  - Electric charges $\vec{Q}$
- Absorbent all matter and energy
  - We cannot screen gravitational force
- Singularity in the center of the black holes. Singularity hidden by the event horizon (Penrose and Hawking)

Seeing black holes

Deux forces règnent sur l'univers : lumière et pesanteur.
(Simone Weil, « La pesanteur et la grâce »)

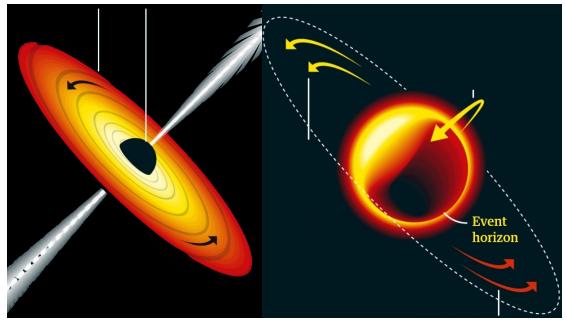
April 10 2019 the « Event Horizon Telescope » has published the « shadow » of the black hole in the centre of the galaxy Messier 87 in the Virgo constellation



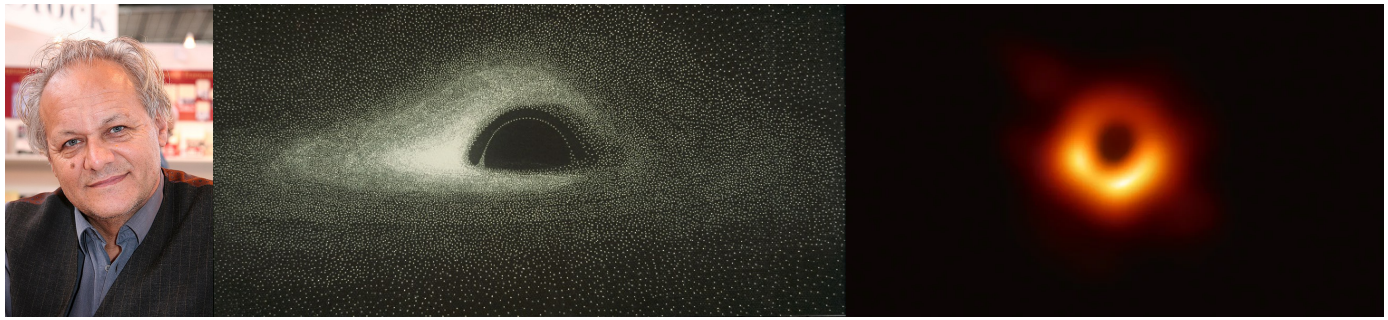
- Mass of 6.5 billion of solar masses
- Distance 55 millions of light-years

Seeing black holes

Accretion disc surrounding the black hole



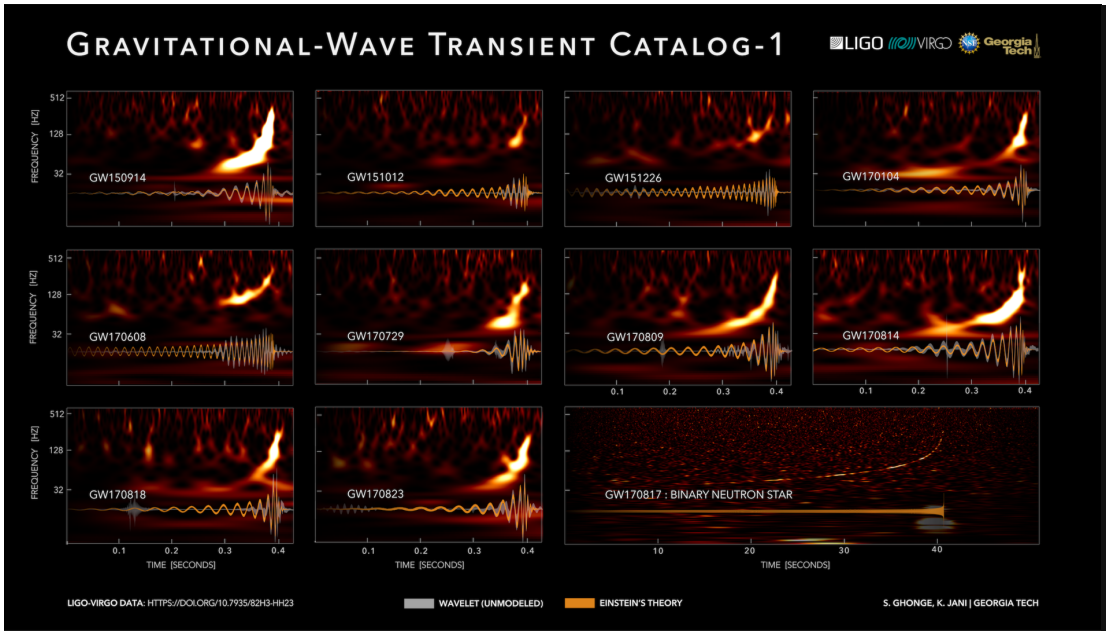
Computed for the first time by Jean-Pierre Luminet in 1979.
The picture appeared in the movie Interstellar

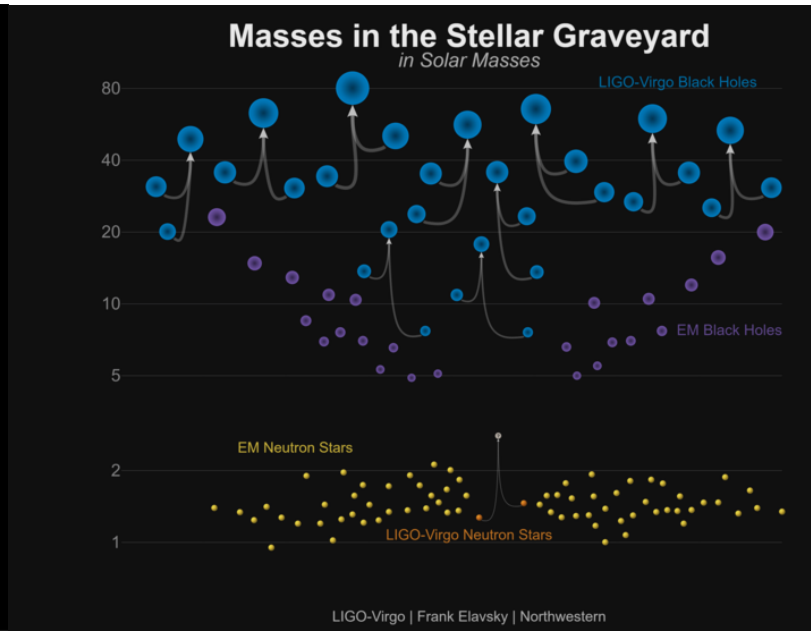


The form of the shadow is compatible with Einstein theory of gravity. The deformation of the image show this is a Kerr rotating black hole

Hearing black holes

Since September 14 2015 LIGO and VIRGO have detected 10 gravitational wave signal from black holes mergers





- Provides information on the dynamics of black holes
- Relatively small black holes between 6 and 40 solar masses
- Soon there should more than a detection per month

How many black holes in the Universe ?


Science News Letter *for January 18, 1964*

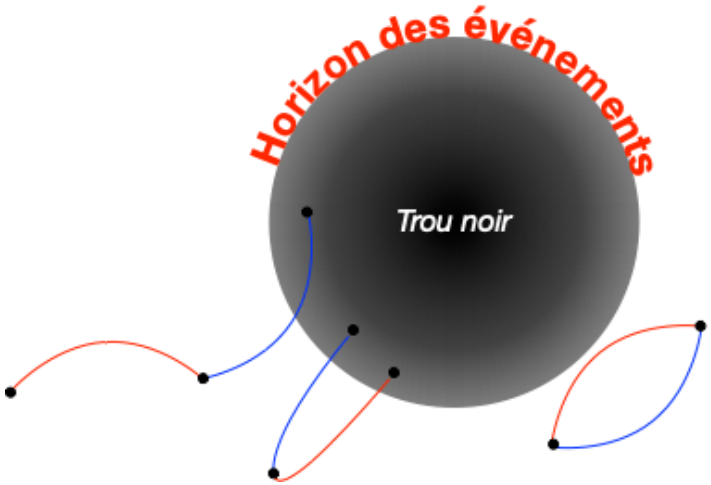
ASTRONOMY

"Black Holes" in Space

- More than 100 millions of black holes of a solar mass in our galaxy
- At least 100 billion of super-massive black holes in our Universe (millons or billion of solar masses)
- Every second a black hole is formed in a supernovæ
- The biggest known black hole is in the Galaxy NGC4889 : 21 billion of solar mass
- The closest known black hole is V4641 Sgr located at 1600 light-year from Earth

Hawking evaporation

In 1975 Stephen Hawking discovered that black hole emit quantum radiation produced near its event horizon



Typical black body radiation with a temperature

$$T_{BH} = \frac{\hbar c^3}{8\pi k_B G M_\bullet}$$

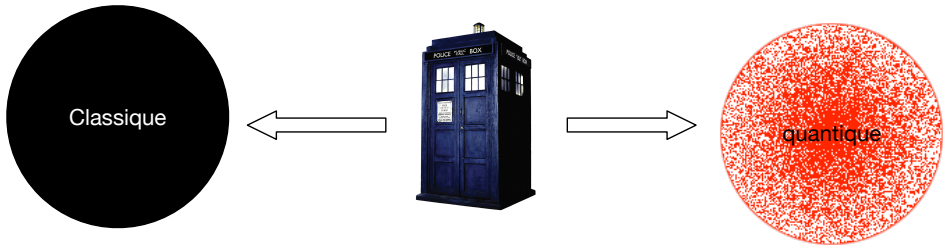
$$T_{BH} = 6.17 \times 10^{-8} \frac{M_\odot}{M_\bullet} \text{ Kelvin}$$

The smaller the black hole the higher the temperature

Evaporation time of a black hole

$$\tau = \left(\frac{M_\bullet}{10^{12} \text{kg}} \right)^3 13.8 \text{ billion years}$$

Black hole entropy



From Hawking temperature one can determine the entropy of a black hole

$$dS_{Schw} = \frac{d(Mc^2)}{T_{BH}} = d\left(\frac{k_B}{4\ell_p^2}\left(\frac{16\pi G^2 M^2}{c^4}\right)\right)$$

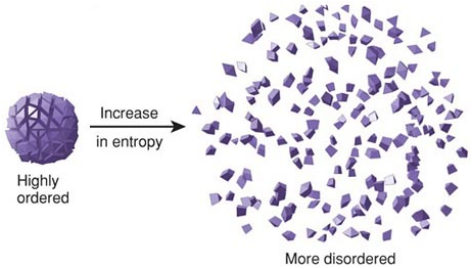
$$S_{BH} = \frac{k_B A}{4\ell_P^2}; \qquad \ell_P^2 = \frac{G\hbar}{c^3} = (1.6 \times 10^{-35}\mathrm{m})^2$$

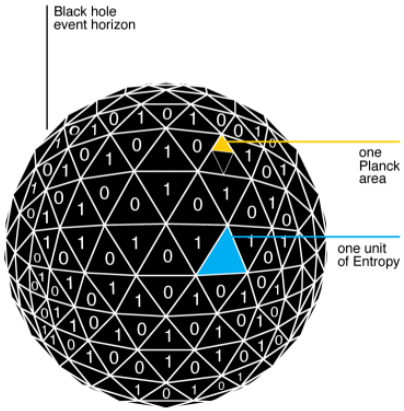
The 2nd principle of thermodynamic imply that the entropy should increase :

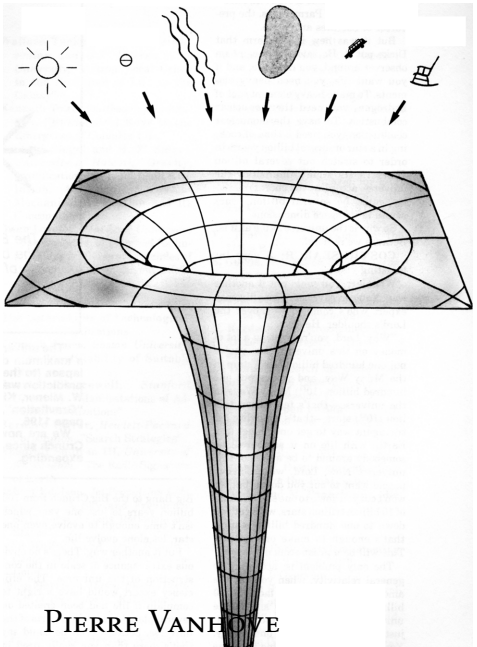
Compatible with gravitational waves observations

$$S_{BH} + S_{GW} \simeq S_{BH} \geq S_{BH_1} + S_{BH_2} \Longrightarrow \overset{=62^2}{A(BH)} \geq \overset{=36^2}{A(BH_1)} + \overset{=29^2}{A(BH_2)}$$

Black hole Entropy







Boltzman's formula relates the entropy to the number of configurations of a system

$$S = k_B \log \Omega$$

For black hole the entropy is huge

$$S_{BH} = \frac{k_B A}{4\ell_P^2} \simeq \begin{cases} 10^{77} \text{for } M_\bullet = M_\odot \\ 10^{90} \text{for black hole Sagittarius A*} \end{cases}$$

The entropy of a solar mass black hole is much higher than the one of the Sun
A classical black hole has only one state

$$S_{classique} = 0 \Longleftrightarrow \Omega_{classique} = 1$$

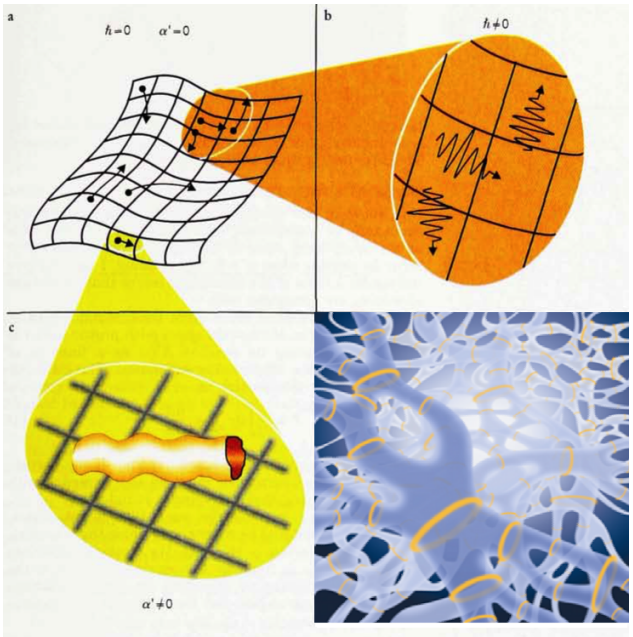
What's going on ?

Black hole entropy paradoxes

EINSTEIN ATTACKS
QUANTUM THEORY

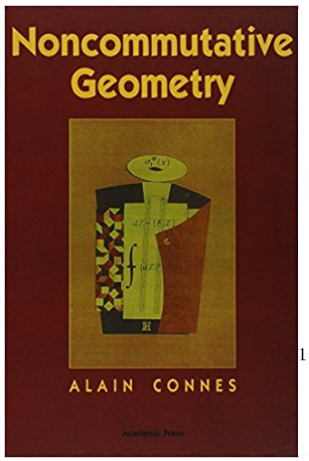
- ? If the black hole evaporates its entropy should decrease
  - ☹ *Violate the second principle of thermodynamics*
- ? If the black hole disappears totally by evaporation
  - ☹ *This violate unitarity of quantum mechanics*
- ? If there is a remnant of black hole
  - ☹ *Quantum mechanical unstable : contrary to current observations*
- ? Where Hawking's radiation comes from ?
  - ☹ From inside the black hole : forbidden by causality
  - ☹ Duplication of quantum information inside and outside the black hole ? *This violates the rules of quantum mechanics*

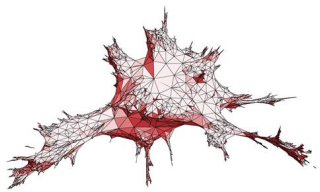
What should we do?

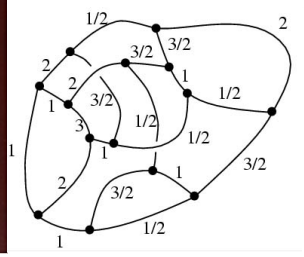


Should we change the theory of gravity by quantum effects

This is the philosophy of string theory



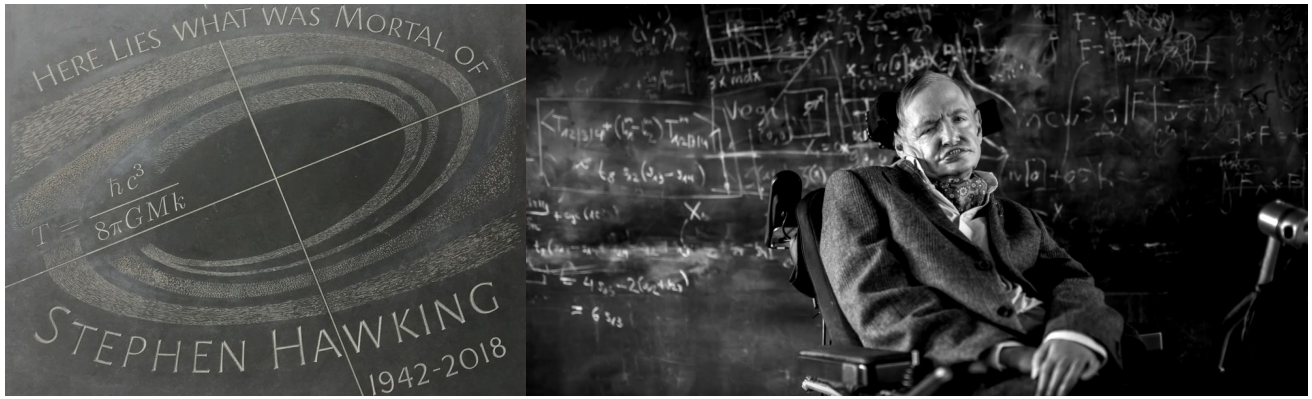




Should we keep Einstein's gravity and modify quantum theory?

This is the philosophy of loop quantum gravity, non-commutative geometry, etc.

Black holes push theories to their limits



Till the end of his life Hawking worked on the problem of quantum black hole

In the posthumous article « **Black hole and soft hair** » [1810.01847] with Malcolm Perry and Andrew Strominger he proposed that quantum information is stored in the gravitational field surrounding the black hole

- This « quantum halo » can affect light surrounding the black hole affecting the shadow of black holes
- Gravitational waves signal should give some indication of the degree of freedom of black holes

(c) A Sky Full of Ghosts - DeLuce Art