Mysterious black holes

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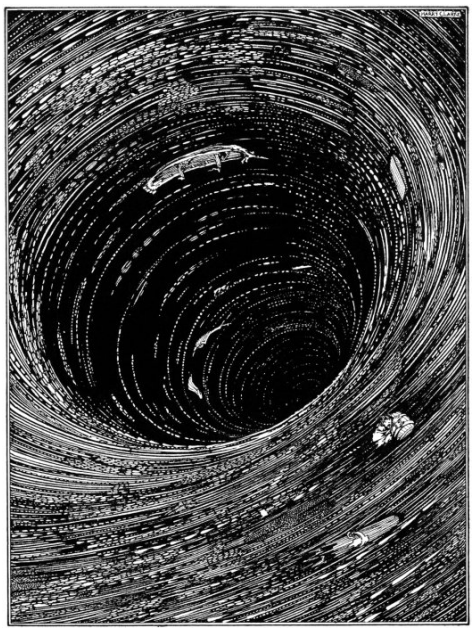
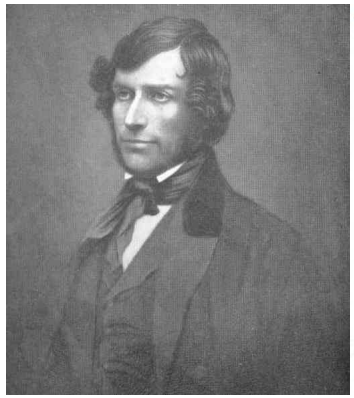
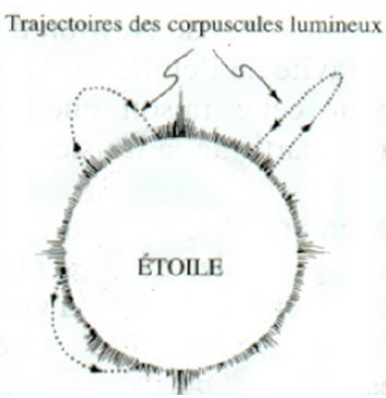
Black Holes



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)





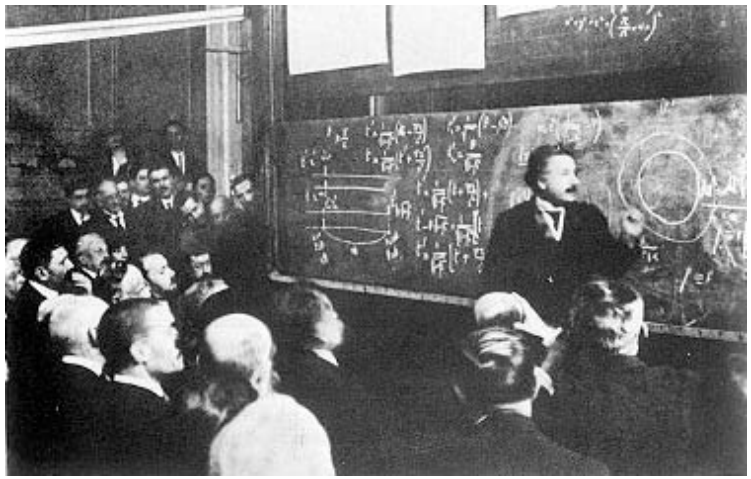
In 1784 the reverent John Michell introduced the **dark star : a very massive object from which light cannot escape**
Pierre-Simon Laplace states in « Exposition du Système du Monde »

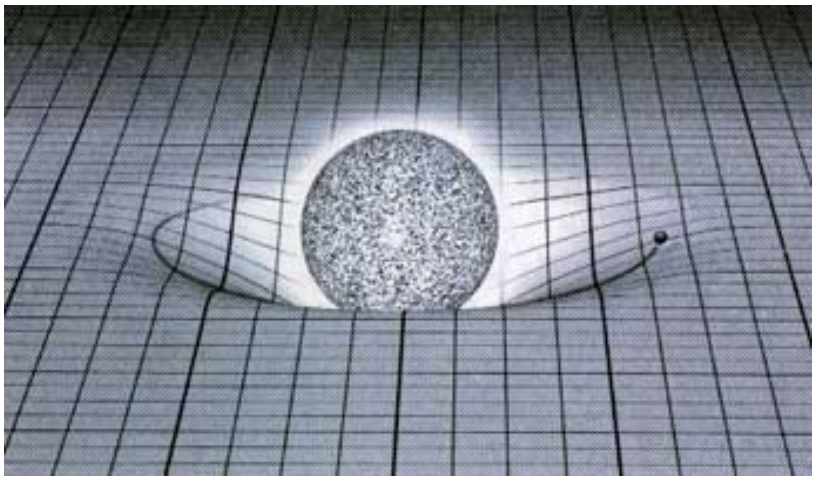
> « *Un astre lumineux, de la même densité que la Terre, et dont le diamètre serait 250 fois plus grand que le Soleil, ne permettrait,* ***en vertu de son attraction, à aucun de ses rayons de parvenir jusqu'à nous.*** *Il est dès lors possible que les plus grands corps lumineux de l'univers puissent, par cette cause,* ***être invisibles.*** »

These ideas were largely ignored and had to wait Einstein's theory of gravity for being firmly established as **black holes**

Gravity is the curvature of spacetime

On November 25, 1915, Einstein formulates general relativity





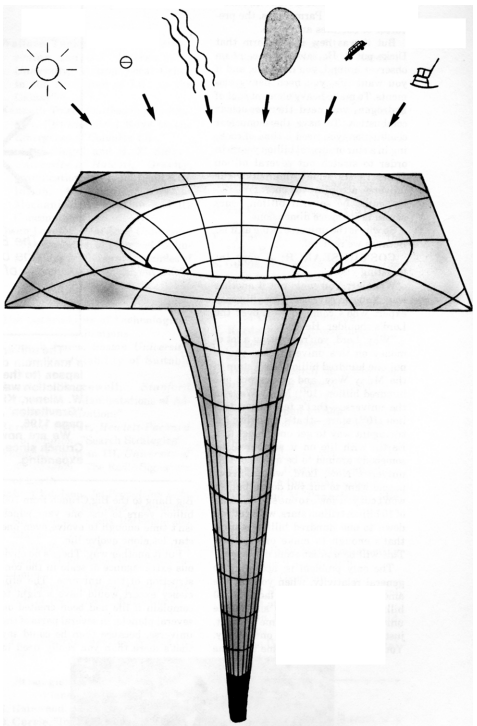
The entire space is the stage of the gravitational field :

Gravity arises from the deformation of spacetime.

A body is not attracted by another body but moves freely in curved spacetime

The most perfect objects

The black holes of nature are 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)



The no-hair theorem : the black hole forget about details of what they swallow

- they are only characterised by
  - their mass $M_\bullet$
  - their angular momentum (how much they rotate)
  - electric charges
- The « center » of the black hole has a singularity hidden from us by an horizon of event

Einstein contested the reality of black holes

ON A STATIONARY SYSTEM WITH SPHERICAL SYMMETRY CONSISTING OF MANY GRAVITATING MASSES

By Albert Einstein

(Received May 10, 1939)

If one considers Schwarzschild's solution of the static gravitational field of spherical symmetry

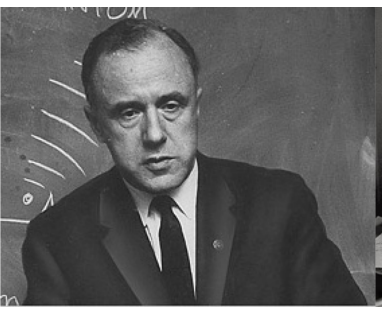
$$(1) \qquad ds^2 = -\left(1+\frac{\mu}{2r}\right)^4 (dx_1^2+dx_2^2+dx_3^2) + \left(\frac{1-\frac{\mu}{2r}}{1+\frac{\mu}{2r}}\right)^2 dt^2$$

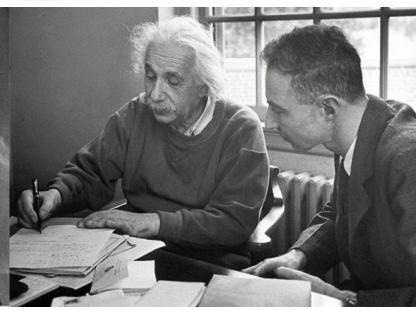
sents the gravitating mass.)

There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing g_{44} do not exist in cases which have physical reality. Schwarzschild himself investigated the gravitational field which is produced by an incompressible liquid. He found that in this case, too, there appears a region with vanishing g_{44} if only, with given density of the liquid, the radius of the field-producing sphere is chosen large enough.

This argument, however, is not convincing; the concept of an incompressible liquid is not compatible with relativity theory as elastic waves would have to travel with infinite velocity. It would be necessary, therefore, to introduce a compressible liquid whose equation of state excludes the possibility of sound

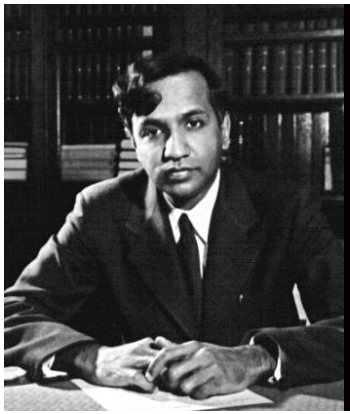
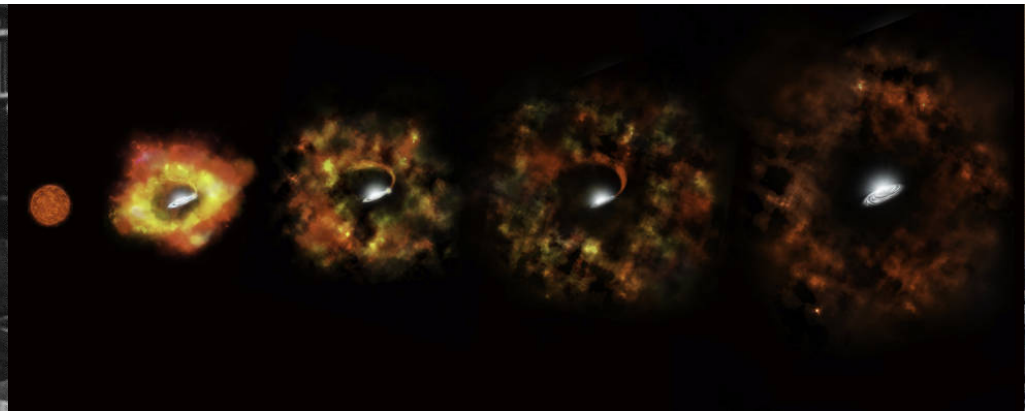
A. Einstein, Annal of Math. 40 4 (1939) 922-936





- In 1939, Einstein argues that black holes are **not compatible** with the **physical reality** of this theory of gravitation.
- Is the singularity real or a mathematical artefact?
- How can Nature create black holes?
- In the 1950s Robert Oppenheimer and John Wheeler, suggested that black holes can **exist** in the Universe

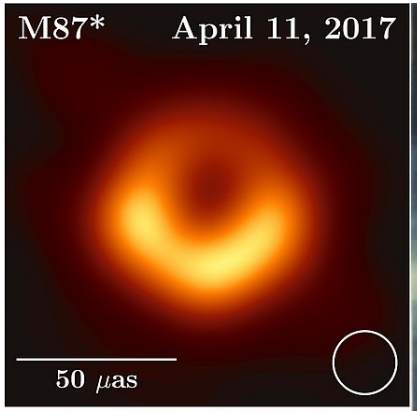
Black holes from collapsing stars

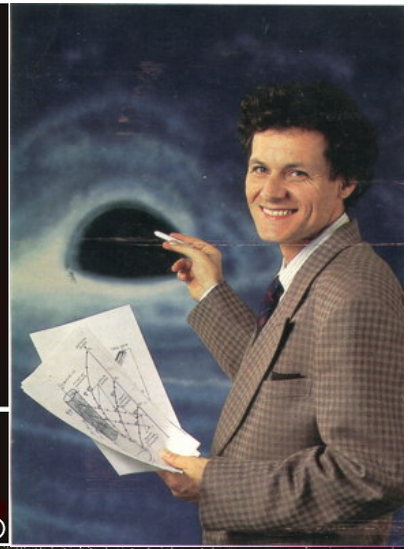



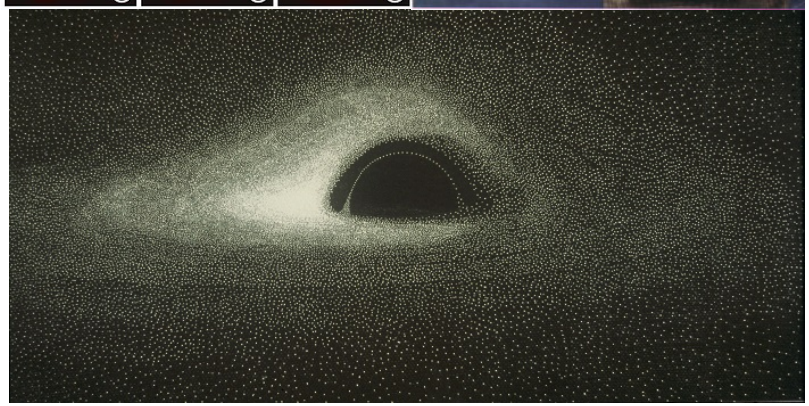

Subrahmanyan Chandrasekhar (Nobel 1983) and Roger Penrose (Nobel 2020) explained that sufficiently massive stars at the end of their lives, having depleted their nuclear fuel, must gravitationally collapse to become a singularity of space-time.

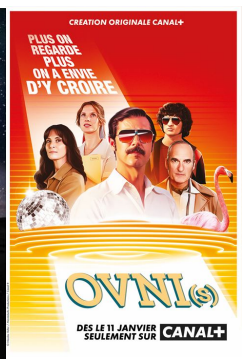
This means concentrating infinite density at a single point where space, time, and **the known laws of physics cease to exist.**

Seeing black holes : M87* (April 10, 2019)









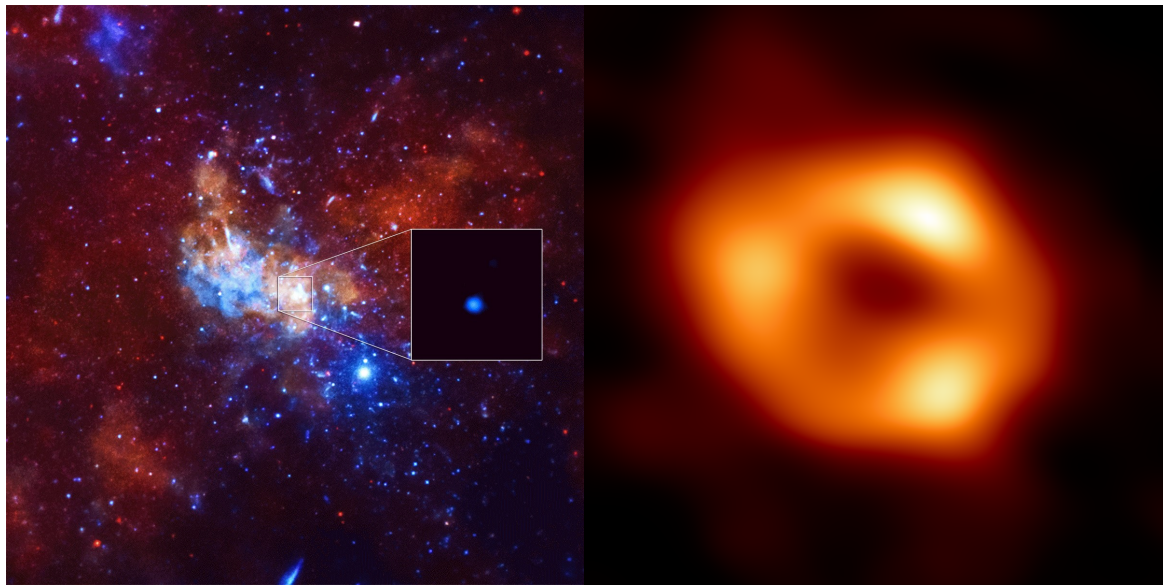
- The first image of a black hole by the « Event Horizon Telescope » collaboration
- Mass $M_\bullet = 6,5$ billions $M_\odot$
- Radius $R_\bullet = 54\,571\, R_\odot$
- Distance 55 millions light years

First computed by Jean-Pierre Luminet in 1979 with an IBM 7040 computer using 1960 punch cards. This image appeared in the film Interstellar and in OVNI(s) saison 2, 1 épisode

Seeing black holes : Sagittarius A* (May 15, 2022)

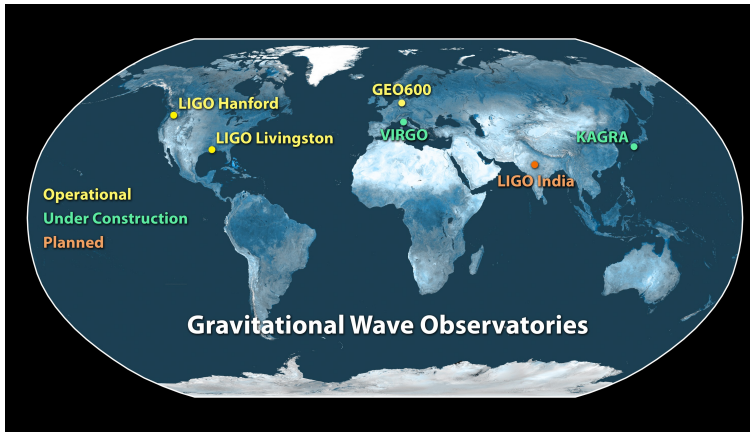
*Sagittarius A** at the centre of our galaxie mass

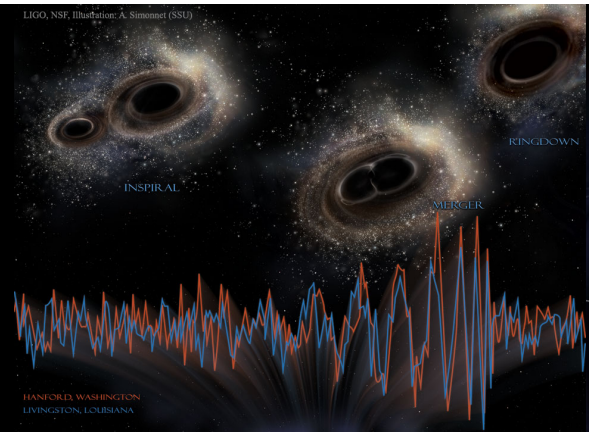
$M_\bullet = 4,152$ millions $M_\odot$, $R_\bullet = 12,264$ millions km $\simeq 18\, R_\odot$

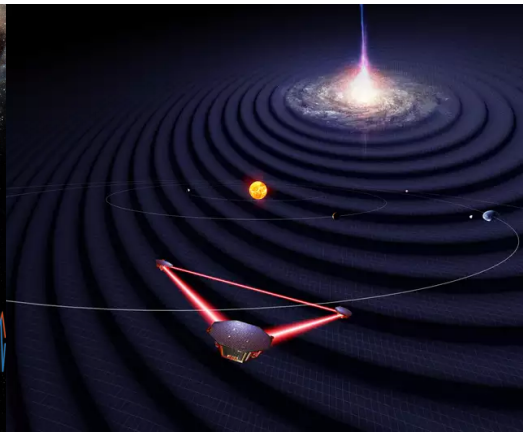


First detected in February 1974 from his radio emission, but the presence of a supermassive black hole at the center of our galaxie was confirmed by the images from the « Event Horizon Telescope » collaboration

Hearing Black Holes (September 14, 2015)







Sound

- More than 90 gravitational waves signal detected by the collaboration LIGO/VIRGO/KAGRA has detected
- First time detection of the **dynamics** of black holes
- New way to probe the properties of space-time and our Universe
- In the near future we expect one detection par week

How many black holes in the Universe ?

Science News Letter *for January 18, 1964*

ASTRONOMY

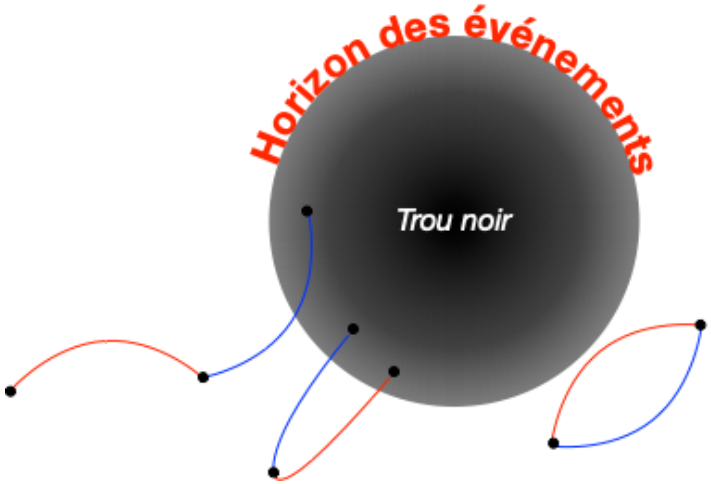
"Black Holes" in Space

Although Einstein doubted the reality of black holes, numerous direct and indirect detections confirm their presence in our observable Universe.

- More than 100 million black holes with a solar mass in our galaxy.
- At least 100 billion supermassive black holes (millions or billions of solar masses) in the universe.
- Every second, a black hole is formed in a supernova.
- The largest black hole is in the galaxy NGC4889 : its mass is 21 billion times that of the Sun.
- The closest known black hole to Earth is a binary system located approximately 3,000 light-years away from Earth.

Quantum black holes

In 1975 Hawking discover that black hole emits a quantum radiation due to its perturbation of the quantum fluctuation near his event horizon



- Evaporation time :

$$\tau = \left(\frac{M_\bullet}{10^{12}\text{kg}}\right)^3 \underbrace{13.8 \text{ billion years}}_{\text{Age of the universe}}$$

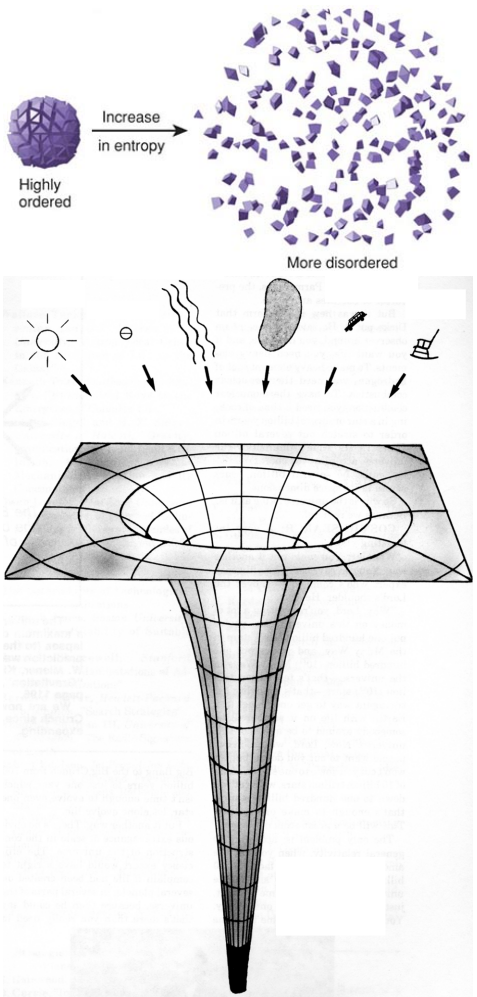
- Temperature

$$T_\bullet = \frac{M_\odot \simeq 2 \times 10^{30}\,\text{kg}}{M_\bullet} 0.12 \mu K$$

- Entropy

$$S_{BH} = \frac{k_B \text{Area}}{4\ell_P^2}$$

Black Hole entropy



Entropy measures the level of disorder $S = k_B \log \Omega$

- A perfectly ordered system has $\Omega = 1$ then $S = 0$
- A shuffled deck of cards $\Omega = 52! \simeq 8 \times 10^{67}$ then $S \simeq 156.36 \times k_B$

Classical black holes have one state and no entropy

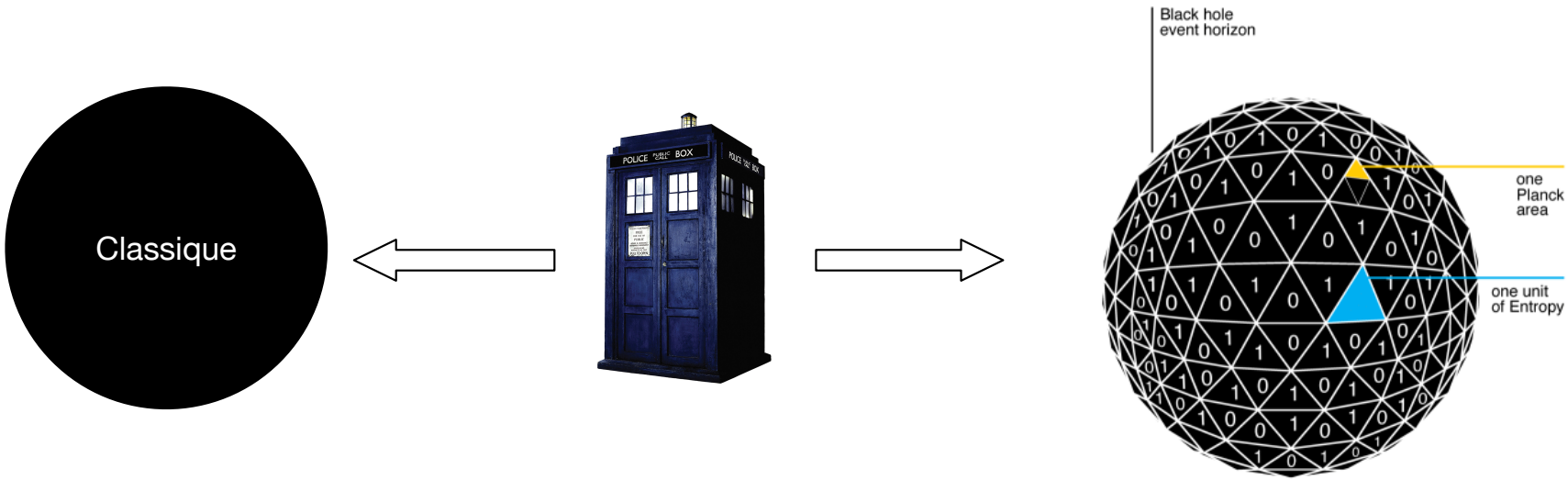
$$\Omega_{\text{classical}} = 1 \Longleftrightarrow S_{\text{classical}} = 0$$

For a quantum black hole, the entropy is enormous

$$S_{BH} \simeq \begin{cases} 10^{77}\ k_B & \text{for } M_\bullet = M_\odot \\ 10^{90}\ k_B & \text{for Saggitarius A}^* \end{cases}$$

$$S_{\text{Sun}} \simeq 10^{56} k_B < S_{BH} < S_{\text{universe}} \simeq 10^{109}\, k_B$$

Black Hole entropy



Curiously the entropy of black holes increases with their area not their volume $S_{\mathrm{BH}} = \frac{k_B \mathrm{Area}}{4\ell_P^2}$

DOCTOR (4th) : Yes. The second law of thermodynamics is taking its toll on the old thing. Entropy increases.

ADRIC : Entropy increases ?

DOCTOR : Yes, daily. **The more you put things together, the more they keep falling apart, and that's the essence of the second law of thermodynamics and I never heard a truer word spoken.** Come on. Come on. (Doctor Who, Logopolis)

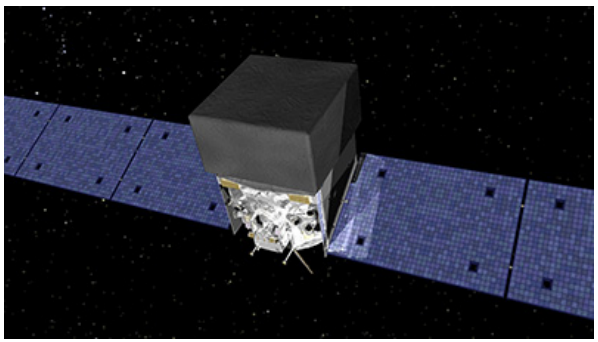
If black holes evaporate due to quantum effects, then they are no longer black.

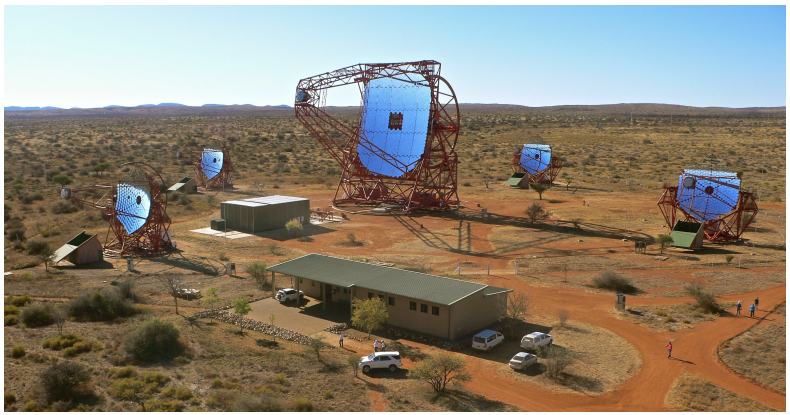
> « The absence of event horizons mean that there are no black holes – in the sense of regimes from which light can't escape to infinity. » (Stephen Hawking)

Detecting Hawking radiation?

The Astrophysical Journal, 857:49 (11pp), 2018 April 10 https://doi.org/10.3847/1538-4357/aaac7b

Search for Gamma-Ray Emission from Local Primordial Black Holes with the *Fermi* Large Area Telescope



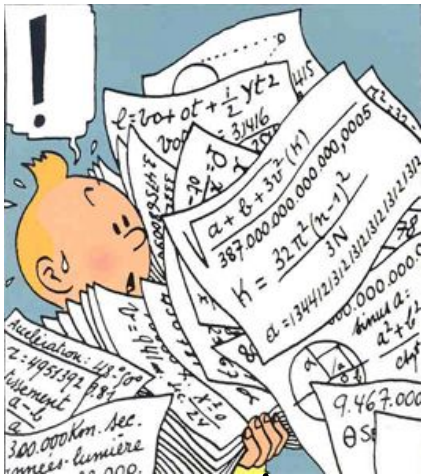


Small black hole evaporate quickly therefore one could detect their Hawking radiation.

A system of imaging atmospheric Cherenkov telescopes and the Fermi Gamma-ray Space Telescope searches for observational evidence of the existence and evaporation of primordial black holes by observing gamma-ray bursts associated with their end of life.

As of Jan 1st, 2023, none have been detected

Paradoxes of Black Hole Evaporation



? If the black hole evaporates, its entropy decreases

☹ *This violates the second law of thermodynamics*

? If the black hole completely disappears after evaporation

☹ *This violates the rules of quantum mechanics*

? If the black hole doesn't completely disappear

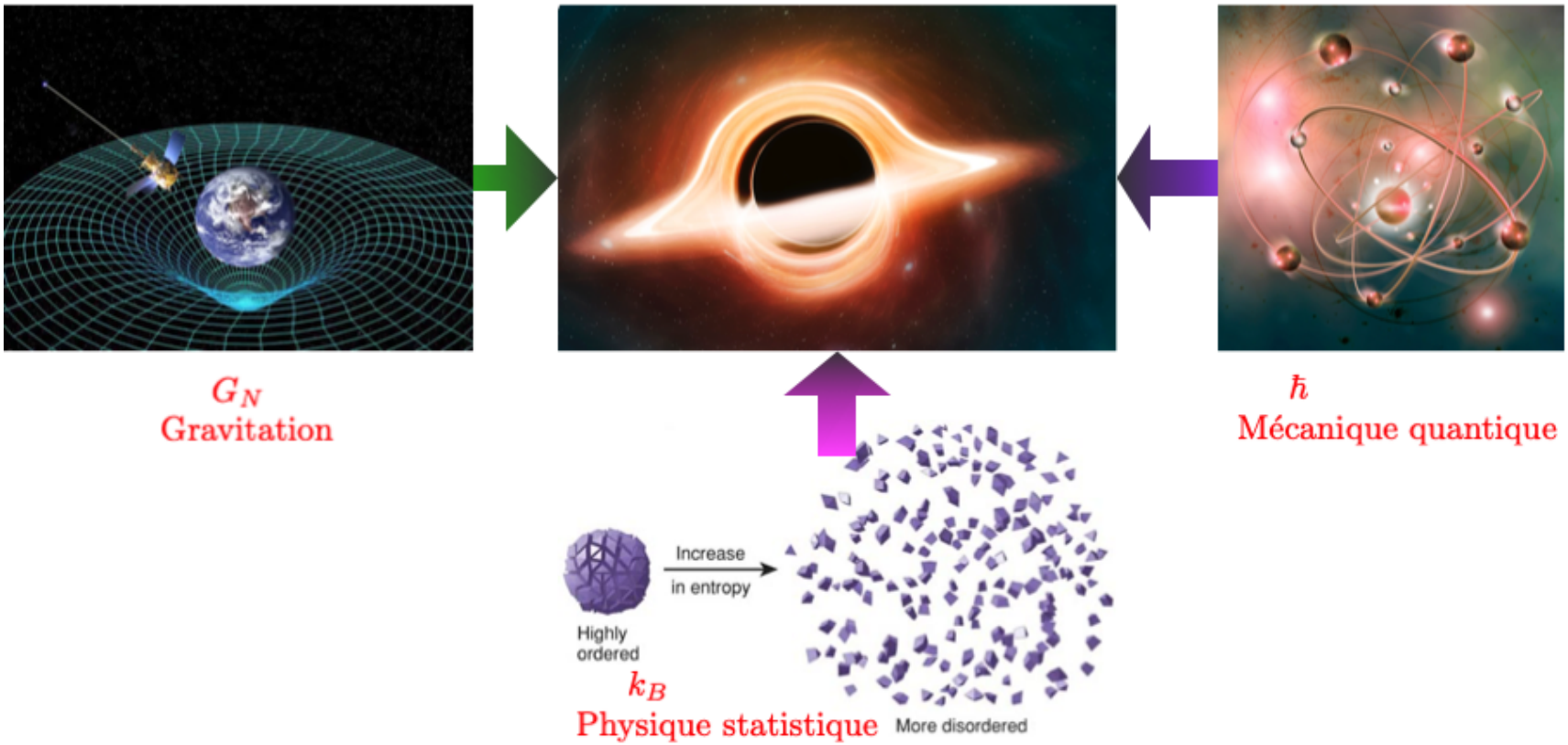
☹ *Quantum instability : contrary to observation*

? How does Hawking radiation escape from the black hole ?

☹ Outgoing signals from the black hole : forbidden by causality

☹ Two copies of the information outside and inside the black hole ? *This violates the rules of quantum mechanics*

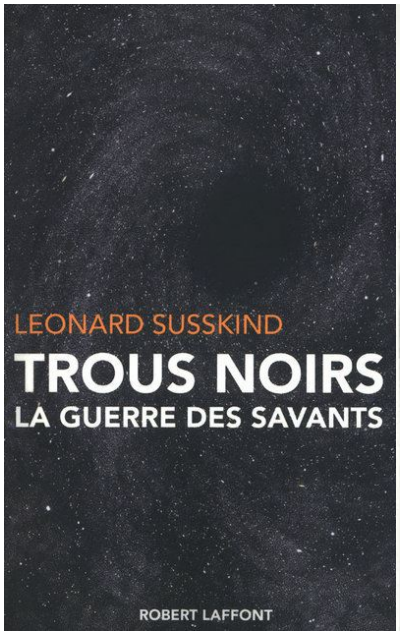
Black holes : theory pushed to its limit

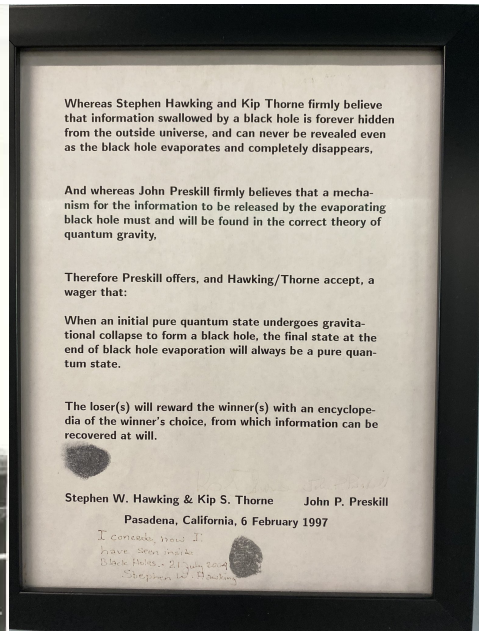


The physics of black holes pushes the limits of our understanding of gravity G_N, quantum mechanics $\hbar$, and thermodynamics k_B.

The black holes war

These paradoxes have sparked *"the black hole war"*, where scientists vehemently oppose each other's viewpoints



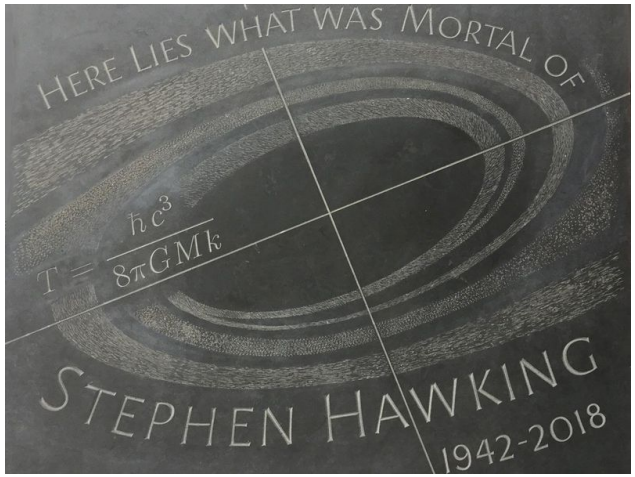


In 2004, Hawking conceded his bet made in 1997 with John Preskill, acknowledging that Hawking radiation can come from inside the black hole and thus provide information about the formation of the black hole.

Kip Thorne (Nobel 2017) did not concede the bet, considering that Hawking's reasoning needs to be confirmed.

Stephen Hawking (1942-2018)


(c) A Sky Full of Ghosts - DeLuce Art



Stephen Hawking has profoundly changed the way we think about black holes, our universe, and the nature of spacetime

A message of hope from Stephen Hawking was sent towards the black hole $1A0620-00$, which has a mass of $6.6M_\odot$ and is located 3500 light-years away.

We remember Isaac Newton for answers, we remember Hawking for questions. (Kip Thorne)